ELECTRIC POWER STATIONS

By

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To
N. J. C.
and
M. I. C.

FOREWORD

by the late SIR LEONARD PEARCE,
C.B.E., D.Sc., M.I.C.E., M.I.Mech.E., M.I.E.E.

In the present days ot stress, the minds and energies of Engineers are turned to many urgent tasks and the relative importance of many factors in the various problems which confront them have had to be readjusted temporarily to suit War conditions. However, when these unnatural conditions have passed and the days of peace return, there will be much reconstruction work to be done and Engineers will be called upon to play just as important a part as at present.

It is therefore essential that even in these strenuous days the technical studies of constructive engineering problems should not be lost sight of and that every effort should be made to keep abreast of modern thought.

The present book by Mr. T. H. Carr on "Electric Power Stations" (Volume 2) is therefore particularly welcome at this time and it constitutes a most interesting review of the latest practice in design of power station plant, dealing more especially with the electrical side of the subject.

I feel sure that the book will be found to be of interest by the experienced engineer and the student alike and one particularly valuable aspect of the book is the extensive bibliography which is given at the end of each chapter, which will enable the reader to continue his researches in still further detail if he requires more data on any particular subject than that which has already been given in the book.

The advances which have been made in power station design since the beginning of this century are almost staggering and it is necessary sometimes to have a reference book in order to keep up to date with latest developments in the many fields. So great have been the advances in the many branches of engineering involved in the construction of electric power stations, that there has been a

great tendency for individual Engineers to specialise in a particular branch, but one important attribute of a good engineer is to have breadth of view, and the present book will, I am sure, be of great assistance in enabling specialists to maintain contact with branches of engineering other than their own.

AUTHOR'S PREFACE

In these days of rapid electrical development the power station is probably the most important part of an electricity supply undertaking. The interconnection of a number of stations tends to reduce its relative importance, but nevertheless sight must not be lost of the inconveniences resulting from failure. The development can be divided broadly into three sections—industrial, commercial and domestic, the latter having progressed beyond all expectations in some countries.

The widespread use of electricity for the benefits of the community has been made possible by the continued efforts of engineers to take full advantage of its possibilities.

Its advantages are well known, and it is the duty of engineers to give an abundant and reliable supply of electricity at a price consistent with the economic standards prevailing. The transmission of large amounts of electrical power over wide areas is economical and practicable, and this in turn has had a decided effect on the choice of power station sites. The continual advances in generation, transmission and distribution plant also play important parts in power station design.

Power station design, unlike many other branches, calls for a wide knowledge of almost every branch of engineering, and in particular the Electrical, Mechanical and Civil sections. Every art and science is built up on first principles and it is only by their successful application that continued progress will be made. The duty of the designer is to choose from the plant available that which best fulfils the conditions to be met and to arrange it in the most economical way; always keeping in mind the necessity for subdivision of plant and abnormal conditions of operation, together with the possible dislocation due to failure of certain items or sections of plant. There are many ways in which the various items may be arranged in relation to one another, and the designer should reduce the subject to an economical association of essential principles.

The question of plant reliability must also be kept in mind, but it can be safely stated that the progress made during the past quarter of a century has resulted in remarkable improvements.

Power station plant has since its inception benefited by the

progress made in marine practice, and it is fitting to add the words of Mr. Churchill (now Sir Winston), then First Lord of the Admiralty, when introducing the Navy estimates in the House of Commons on Tuesday,

"In the last war I had a stream of lame ducks coming to dock for 'condenseritis,' or heated bearings, but now they seem to steam on almost for ever."

This book deals with the general principles governing design, construction and operation. A brief survey of the materials used and the construction of many items of plant and equipment are given primarily for reference purposes.

There are numerous excellent books and papers giving detailed descriptions of the majority of the plant used for power station service and no useful purpose would be served by including such descriptions. To simplify descriptive matter a large number of diagrams and sketches are included. Few books, however, deal with power station design, construction and operation. The author undertook the preparation of the present volumes at the request of the publishers, who felt that there was a need for such a publication. It is hoped that the book will prove useful to power station engineers, consulting engineers, designers, operatives, students and others.

The author wishes to express his sincere thanks to Sir Leonard Pearce for writing the Foreword to this book.

Grateful acknowledgments are also made to the editors of *The Electrical Review*, *Electrical Industries*, *Engineering and Boiler House Review*, *Power and Works Engineer*, *The Draughtsman*, *Electrical Engineer*, *Electrical Times*, *Mining Electrical Engineer*, and *Engineer Surveyors' Journal* for permission to use the author's articles which have appeared in their journals from time to time.

Free reference has been made to standard specifications and also published transactions of scientific institutions.

The final tracings of nearly all the drawings and diagrams have been the work of Mr. C. Brooke.

Finally the author wishes to express his appreciation of the assistance afforded him by the supply of information and illustrations from many individuals, electricity undertakings and manufacturers.

T. H. CARR.

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CHAPTER X

CONDENSING PLANT

THE primary functions of a condensing plant are :—

(1) To extract a sufficient amount of heat from the steam exhausted into it and condense the steam completely.

(2) To reduce the exhaust steam pressure by condensation of the steam, *i.e.*, to create a vacuum, thus freeing the maximum amount of expansion energy for the performance of useful work.

(3) To remove the condensed steam from the condenser and return it to the boilers at the maximum possible temperature for re-evaporation.

(4) To extract air and incondensable gases which enter the condenser with the exhaust steam, also *viâ* tappings from the evaporators and feed heaters, and air which leaks into the feed water system.

An efficient condensing plant must be capable of producing and maintaining a high vacuum with the temperature and quantity of cooling water available (bearing in mind capital cost and pumping power), and be designed to operate for prolonged periods without trouble.

The desirable features are :—

(1) Minimum quantity of circulating water.

(2) Minimum cooling surface per kW.

(3) Minimum auxiliary power.

(4) Maximum steam condensed per sq. ft. of surface and heat transfer.

The effect of low vacuum is very pronounced for it limits the output of a turbo-alternator and necessitates greater plant capacity to meet all operating conditions. Taking one example : a 20 MW set which normally operates at a vacuum of 29·0 in. Hg. (cooling water 55° F.) may show the following figures :

(1) 17 MW—27·5 in. Hg. (60° F.).

(2) 20 MW—28·8 in. Hg. (60° F.).

The tubes under the first condition were very slimy and it was impossible to increase the output above that shown. Under the second condition the top half of the condenser tubes had been gunned by rubber bullets and a marked improvement was effected.

The rate of increase of steam consumption per 1 in. fall of vacuum from design turbine condition is between 4 and 5 per cent.

for normal units operating at a vacuum or absolute pressure of about 28·5 in. Hg. The cost of coal per lb. of steam generated has therefore to be considered when determining the permissible fall in vacuum, before condenser cleaning costs are incurred. The efficiency of a turbine depends to a greater extent on the pressure at the exhaust branch than on the high-pressure conditions at the steam inlet. A high water velocity has been found to reduce tube fouling while the rate of heat transfer increases approximately as the square root of the water velocity. Increasing the velocity will result in increased friction head and consequently higher annual cooling-water pumping costs. Further, high water velocity may cause tube erosion, although bell mouthing of tube-ends and ferrules overcomes this. A shallow water box may also be responsible for internal tube erosion.

Before proceeding in detail with the design of the condensing plant it is important that the local conditions be explored to the fullest. So much depends on the cooling water system that full details should be known of river or sea level, quality of water (such as quantity of mud or other matter in suspension), mussel growth, acidity or high alkalinity, and in addition, hardness and cost of make-up water where cooling towers are to be used. The temporary hardness has an appreciable effect on the condenser tube heating surfaces particularly at the hotter portions. In one station the acidity of the river water approaches a pH value of 3·0 due to the presence of mine drainage and precautions had to be taken to prevent corrosion. The condensing system piping is of cast iron coated with bitumastic compounds. and bronze and special alloy tubes are used.

Theoretical Considerations. The complex theories associated with condenser design are beyond the scope of this book but reference to a few items of interest to both constructional and operating engineers will not be out of place.

The work done by the steam on its passage through the turbine is, neglecting losses, the mechanical equivalent of the heat abstracted from the steam while its pressure is reduced from initial to final conditions and the lower the exhaust pressure the greater will be work done per lb. of steam.

Since steam at a pressure of 1·5 lb. per square inch absolute occupies 14,200 times the volume of water from which it was generated, it follows that if the steam be condensed in a closed vessel a partial vacuum will be formed which can be further increased by

removing air and incondensable gases which enter with the steam or leak into the system from other sources.

The amount of heat to be abstracted from the steam in order to condense it, is exactly equal to the latent heat required to evaporate the same weight of water at the pressure corresponding to the temperature in the condenser. In power station practice the abstraction of heat is effected by the transmission of heat through tubes to cooling water.

The relation between pressure and temperature of a mixture of steam and air as it exists in a condenser does not strictly conform with the steam tables but obeys "Dalton's Law," which states that each constituent of a mixture of gases or vapours exerts a pressure equal to that which it would exert if it alone occupied the containing vessel. The pressure of each constituent gas or vapour is known as a partial pressure, and the sum of the partial pressures is equal to the total pressure exerted by the mixture. The volume of air is equal to the volume of steam and the steam temperature corresponds to the partial steam pressure. The steam entering the exhaust

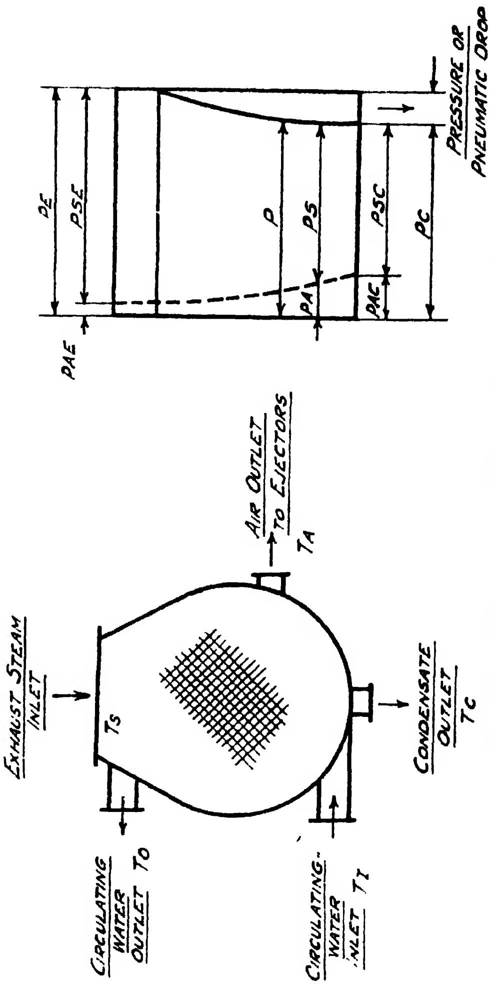


Fig. 316. Steam and Air Pressure in Surface Condenser.

inlet contains about 0·05 per cent. by weight of air which is brought in solution by way of the boiler feed water since the exhaust branch and the turbine itself are reasonably airtight. The partial air pressure is thus negligible so that the total pressure may be regarded as the steam pressure and the temperature of the steam will correspond to the total pressure.

As the steam condenses on its way through the condenser the condensate cools as it falls over the lower nests of cold tubes and the temperature of the air and its vapour being equal to the condensate temperature, the partial steam or vapour pressure at the bottom of the condenser is less than at the top. The partial air pressure is, however, no longer negligible, having been greatly increased, the increase being due to the higher air density caused by cooling and a greater ratio of air to vapour by weight.

These pressure conditions are shown in Fig. 316, from which it will be noted that while the partial air pressure is greater, and the partial steam pressure less at the bottom than at the top, the total pressure is less at the bottom. This drop is necessary to initiate the flow of steam through the condenser. The pressure difference between the exhaust steam inlet and condensate outlet is usually termed the pneumatic or pressure drop. The effect of pressure drop is to necessitate an increase in cooling surface area.

The performance of a condensing plant is ascertained from the vacuum and temperature conditions obtaining at the condenser. Authorities on this subject appear to differ on the definitions of condenser and vacuum efficiency. The performance of a condenser is measured by the absolute pressure maintained at the exhaust branch. The vacuum gauge used measures the pressure difference between that inside the condenser and the outside atmosphere, and as the latter varies with climatic conditions and at different altitudes it is necessary to refer the vacuum to the normal barometric pressure, viz., 14·73 lb. per square inch absolute or 30 in. Hg. at 32° F.

If a U tube containing mercury has one leg connected to the condenser in which a vacuum is maintained, the other leg being open to the atmosphere, the mercury will rise in the leg connected to the condenser until the pressure of the atmosphere is balanced by the column of mercury and the pressure in the condenser. The difference in height of the levels in the respective legs therefore measures the difference of pressure between the inside of the vessel

and the atmosphere, and may be expressed in inches of mercury, 1 in. of Hg being equivalent to a pressure of

$$\frac{1 \times 14{\cdot}73}{30} \text{ or } 0{\cdot}491 \text{ lb. per square inch.}$$

With a vacuum of 26 in. Hg. and barometer 30 in. Hg., the condenser performance would be identical if the vacuum was 22 in. (barometer 26 in.) or 26·5 in. (barometer 30·5 in.), since the absolute pressure inside the vessel in each example is equivalent to the pressure exerted by a column of mercury 4 in. in length, viz., $4 \times 0{\cdot}491 = 1{\cdot}964$ lb. per square inch absolute.

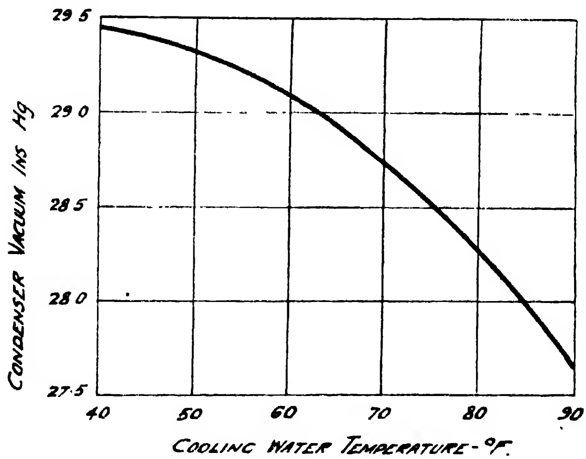


FIG. 317. Effect of Cooling Water Temperature upon Vacua.

One authority (Evans, Steam Condensing Plant ") has suggested the following :—

$$\text{Factor of performance K} = \frac{W \,.\, L}{\theta_m \,.\, S \,.\, V^{\frac{1}{2}}}$$

where W = weight of steam condensed lb. per hour.
L = heat removed per lb. of steam in B.Th.U.
θ_m = mean temperature difference °F.
S = total surface in square feet.
V = water velocity in feet per second.

The value of this factor of performance is about 260 for well-designed condensers operating satisfactorily. It is also suggested that this performance may be used to show faulty operation as lower values than 260 will generally indicate a dirty condenser.

Evans has also suggested another coefficient of performance :—

$$K = \frac{1{,}000}{(T_s - T_o)\,(T_s - T_c + 5)} \text{ per cent.}$$

This takes into consideration water and steam temperature which is an advantage since with these temperature differences the operating engineer is able to determine when and where his plant is at fault.

Fig. 317 shows the effect of cooling water temperature upon Vacua.

Condenser efficiency =

$$\frac{\text{Vac. corrected to 30-in. barometer}}{\text{Vac. corrected to circulating water outlet}} \times 100 \text{ per cent.}$$

This is a measure of the condenser performance as a heat extractor.

Vacuum Efficiency =

$$\frac{\text{Vac. corrected to 30-in. barometer}}{\text{Vac. corrected to condensate temp.}} \times 100 \text{ per cent.}$$

The application will be understood from the figures given :—

Circulating water inlet temperature	70° F.
,, ,, outlet temperature	83° F.
Vacuum (30-in. barometer)	28·5 in.
,, temperature (corrected to 28·5 in.) . . .	91·6 F.
Condensate temperature	89° F.

From steam tables.

Vacuum corrected to 83° F. = 28·87 in.

,, ,, ,, 89° F. = 28·63 ,,

$$\text{Condenser efficiency} = \frac{28{\cdot}5}{28{\cdot}87} \times 100 = 98{\cdot}8 \text{ per cent.}$$

$$\text{Vacuum efficiency} = \frac{28{\cdot}5}{28{\cdot}63} \times 100 = 99{\cdot}4 \quad ,,$$

Results can be finally reduced to 30-in. barometer by use of the following formulæ :

$$V_{30} = 30 - (B_c - V_c)$$

where

V_{30} = vacuum finally corrected to 30-in. barometer and 32° F.

B_c = actual barometric pressure at time of test corrected to 32° F.

V_c = arithmetric average of vacuum manometers at time of test corrected to 32° F.

The absolute pressure at the condensate outlet is always slightly less than at the exhaust steam inlet and the difference (pressure drop across the condenser) between the two should be as small as

possible. In the largest condensers this drop is about 0·1 to 0·15 in. This pressure drop is sometimes referred to as the pneumatic drop and its magnitude depends upon the reduced partial steam pressure the shape and size of condenser and the arrangement of the tube and steam lanes.

As condensers increase in size the banks of tubes through which the steam has to make its way become more dense and impassable. With steam travelling at a velocity of from 300 to 400 ft. per second in a nest of 9,500 tubes, its velocity will be quickly dissipated unless provision is made to prevent this. A large exhaust inlet, a wide shallow shell and a generous pitching of tubes are desirable.

The exhaust inlet is fixed by the turbine designer, the width of the shell will be governed by the site and foundations, and the pitching of tubes is only possible by increasing the size and cost of condenser.

In addition to the loss of effective vacuum caused by the resistance to steam flow, there is a thermal loss from the same cause since the condensed steam leaves at a relatively low temperature. This can be verified from the steam tables. At 29 in. Hg. the corresponding temperature is 79° F. Taking a pressure drop across the condenser of 0·2 in. the corresponding temperature at 29·2 in. Hg. is 72° F., so if the condensate is extracted from this region of the condenser 7° F. is lost, representing approximately 0·5 per cent. of the coal consumption of the unit.

At lower vacua this is not of such importance, for at 28 in. Hg. a pressure drop of 0·2 in. Hg. gives a temperature drop of 3° F. only.

Another feature of importance is the amount of cooling surface required. This depends, among other factors, upon the following :—

(1) The velocity of the cooling water in the tubes.

(2) The temperature of the cooling water.

(3) The condition of the tubes as regards cleanliness.

(4) The arrangement of the steam space.

(5) The quantity of air in the condenser, the capacity and efficiency of the air ejector.

(6) The dimensions of the tubes.

(7) The quantity of steam condensed per unit of surface.

(8) The design of the condenser.

The formula used for estimating the cooling surface is :—

$$S = \frac{WL}{K_1 \theta_m} \text{ per square foot.}$$

where W = total steam condensed in lb. per hour.

L = latent heat of steam in B.Th.U.'s per lb.

θ_m = mean temperature difference between steam and water ° F.

K_1 = rate of heat transmission in B.Th.U.'s per square foot, per ° F. per hour.

WL (B.Th.U.'s) = total heat transferred to cooling water per hour.

$K_1\theta_m$ (B.Th.U.'s) = total heat transferred per square foot of cooling surface per hour.

The temperature difference between cooling water and steam varies throughout the condenser.

The water, as it passes through the tubes, is gradually warmed, while the steam, after condensation, is slightly cooled below vacuum temperature owing to the increasing partial air pressure.

If T_I = cooling water inlet temperature °F.
T_o = ,, ,, outlet ,, ,,
T_s = Exhaust steam temperature ,,
T_c = Condensate temperature ,,

The maximum temperature difference at the bottom of the condenser where the cold water enters is $T_c - T_I$, and the minimum, where the heated water leaves is $T_s - T_o$. The true mean temperature difference is not the arithmetical mean but follows a hyperbolic law and is given by Grashof as :—

$$\theta_m = \frac{(T_c - T_I) - (T_s - T_o)}{\log_e\left(\dfrac{T_c - T_I}{T_s - T_o}\right)}$$

The bulk of the steam is condensed at constant temperature T_s, in which case the equation becomes :—

$$\theta_m = \frac{T_o - T_I}{\log_e\left(\dfrac{T_s - T_I}{T_s - T_o}\right)}$$

Some figures relating to a 30,000-kW. 3,000-r.p.m. turbo-alternator are given :—

Temperature of steam space	= 74° F.
,, condensate	= 70° F.
Cooling water outlet	= 62° F.
,, ,, inlet	= 44° F.
Condenser vacuum (Kenotometer)	= 0·82 in. Hg. approx.
Air suction ,, ,,	= 0·63 in. Hg. ,,

Barometer	= 30·23 in. Hg.
Turbine house temperature	= 82° F.
Load	= 26,600 kW.
Maximum temperature difference	$= T_c - T_I$
	= 70 − 44.
	= 26° F.
Minimum temperature difference	$= T_s - T_o$.
	= 74 − 62.
	= 12° F.

As it is only necessary to condense the steam, only the latent heat L of the steam is transferred or rejected to the cooling water. This is often taken as 1,000 B.Th.U.'s per lb. of steam condensed but may be determined with greater accuracy from the steam tables if the dryness fraction of the steam is known. The question of heat rejected to cooling water in a condenser has been outlined by Guy and Winstanley who contend that it is essential both in the statement and analysis of condenser performance and in the determination of cooling surface required, that the actual amount of heat abstracted must be known and used.

The heat rejected to the condenser per lb. of wet steam h_c can be determined from the formulæ :—

$$h_c = \begin{pmatrix}\text{heat at}\\ \text{stop valve}\end{pmatrix} - \begin{pmatrix}\text{heat converted}\\ \text{into work}\end{pmatrix} - \begin{pmatrix}\text{sensible heat}\\ \text{in condensate}\end{pmatrix}$$

$$= h_1 - \frac{2545}{DN_m} - h_4$$

where h_1 = total heat at stop valve in B.Th.U.'s per lb.
D = steam consumption in lb. of steam per B.H.P.
N_m = mechanical efficiency of the turbine
h_4 = sensible heat of the condensate in B.Th.U.'s per lb.

For most purposes it is sufficient in the case of steam turbines to assume a value of 99 per cent. for N_m for machines of large capacity in relation to their speed of rotation. A figure of 98 per cent. has been suggested for small machines. To show how the heat rejected to the condenser differs from the conventional figure of 1,000 B.Th.U.'s per lb. the following figures are given for large plants :—

1,400 lb. per sq. in.	800° F.,	29 in. vac.	877·10
	,,	28 ,, ,,	875·40

600 lb. per sq. in.	800° F.,	29 in. vac.	913·25
	,,	28 ,, ,,	914·15
200 lb. per sq. in.	550° F.,	29 in. vac.	905·18
	,,	28 ,, ,,	907·08

The method given for determining the heat rejected to the cooling water is also strictly true for systems fitted with air ejectors or for regenerative feed heating systems, providing in both cases that the steam consumption, D, includes the steam for the ejector and that condensed in the regenerative feed heating and that h_4 is the sensible heat of the condensate after the ejector heater or the last feed heater as the case may be. The latter condition requires that the drains from all such heaters return to the condenser and that they are measured with the condensate.

The temperature and quantity of cooling water available determines the maximum vacuum it is possible to obtain, but first cost, auxiliary pumping and screening power, etc., must be considered and the plant designed to give the most economical vacuum. Figs. 318 and 319 show typical relationships to which reference may be made. To produce the necessary flow of heat through the tube walls near the top of the condenser, the temperature of the warm water leaving must be less than that of the steam entering. Suitable average values of this temperature difference $(T_s - T_o)$ are 8° to 10° F.

In deciding upon a value of $(T_s - T_o)$ it is advisable to take into consideration the site conditions regarding the supply of cooling water. If cooling towers are used and the head on the circulating water pump is high, $(T_s - T_o)$ should be a minimum, giving a maximum temperature rise and a minimum quantity of water thereby reducing the auxiliary pumping power to the lowest possible figure.

The mean temperature difference, θ_m, is small, thus increasing the surface area necessary with consequent increase in first cost of condenser.

If there is an abundant supply of water and low pumping heads $(T_s - T_o)$ may be a maximum, resulting in a high mean temperature difference θ_m and a smaller and cheaper condenser consistent with economical pumping power.

For economical operation of a surface condenser as regards pumping costs the ratio $\frac{\text{wt. of cooling water}}{\text{wt. of steam condensed}}$ should not exceed 80 (usually between 60 to 70). This corresponds to a minimum

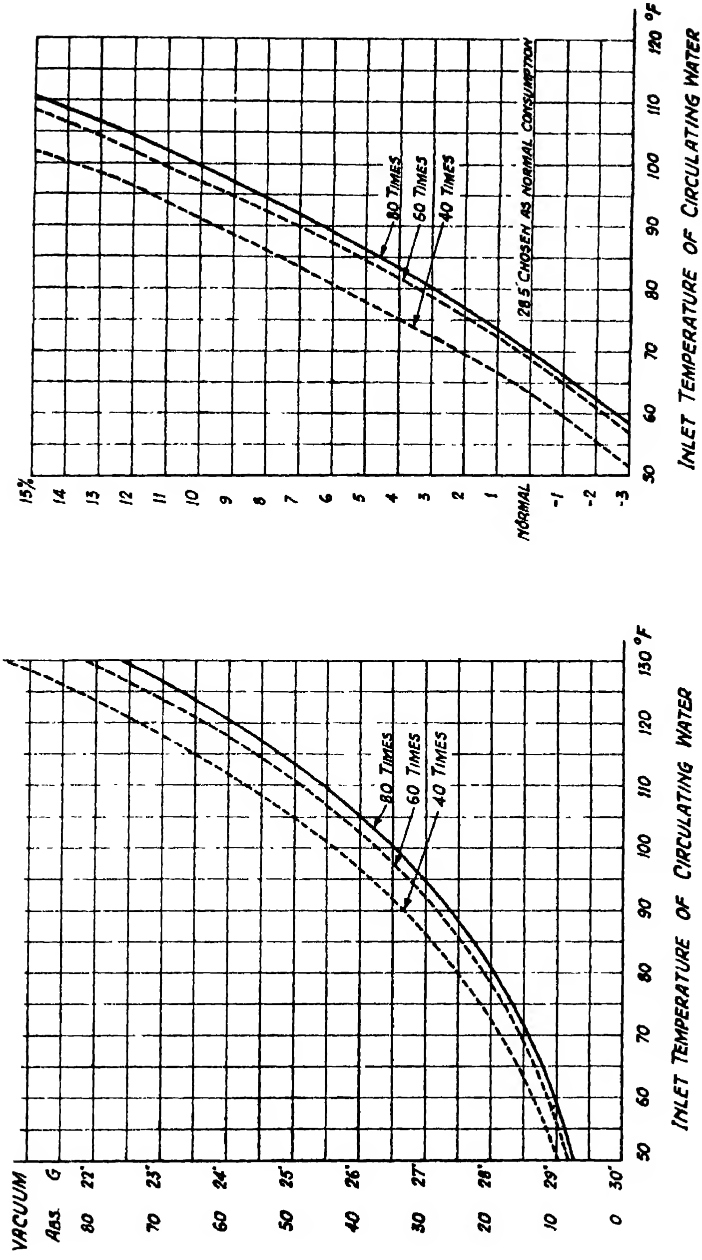


FIG. 318. Loss of Vacuum with Warm Water and Increase in Coal Consumption.

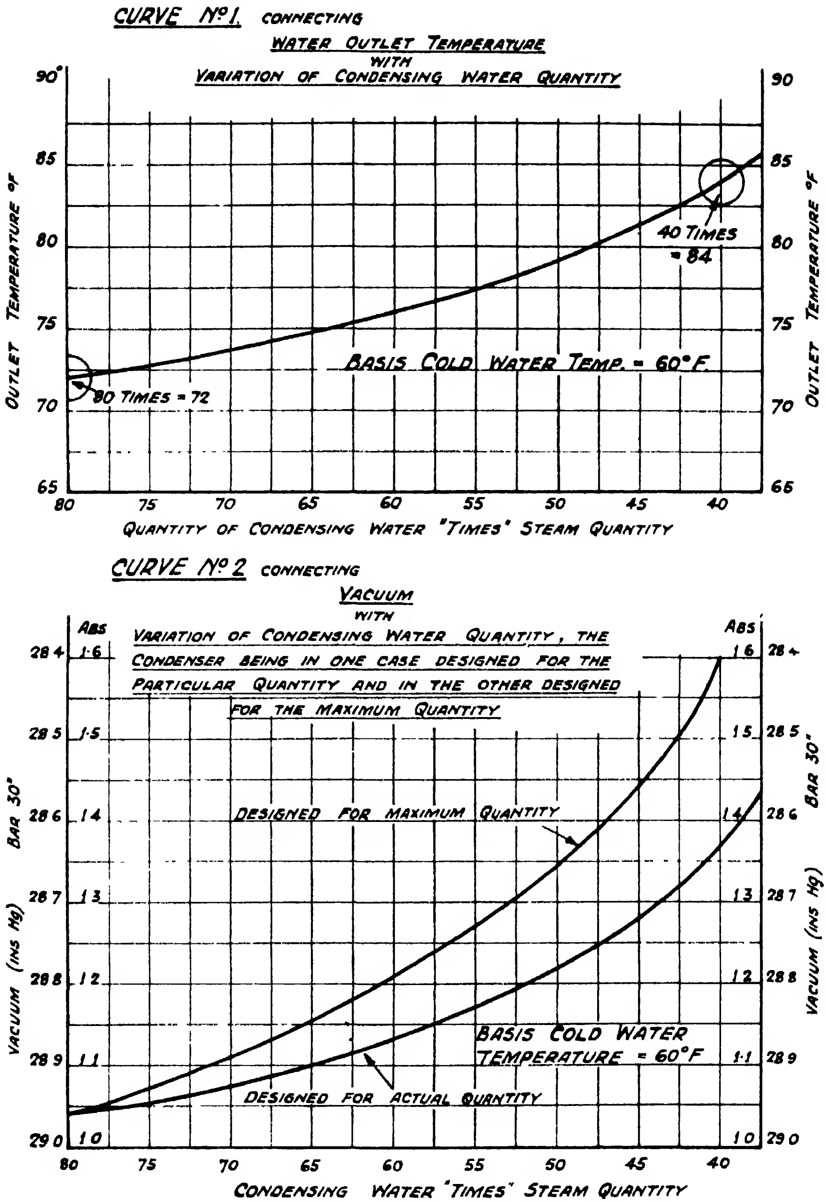


FIG. 319. Relationship between Circulating Water Outlet Temperature, Vacuum and Quantity of Water.

approx. cooling-water temperature rise of $\frac{1,000}{80} = 12{\cdot}5°$ F.

The ratio $\frac{\text{cooling water}}{\text{steam condensed}}$ may also be found from $\frac{L}{T_o - T_i}$.

Given a specified weight of steam to be condensed and a given vacuum to be maintained, the most efficient condenser is one which will do the required duty with the smallest surface (low initial cost consistent with the expenditure for cleaning and maintenance), the smallest quantity of circulating water, the lowest circulating water pumping power, the lowest steam consumption for air-ejecting plant and the highest condensate temperature.

Improvements have been effected by :—

(*a*) Efficient air removal.

(*b*) Changes in tube plate arrangement, configuration of shell, uniform distribution of the steam and its free access to the nest of tubes by reducing the resistance of the flow of steam across the tubes.

These have achieved the following :—

(1) Higher heat transmission rates (600–800 B.Th.U./sq. ft./hr/°F.).

(2) Effective de-aeration with negligible oxygen content due to (3).

(3) A condensate temperature equal to, or within a degree of, the steam temperature corresponding to vacuum.

(4) The smallest temperature difference between the temperature corresponding to the vacuum at the turbine exhaust and that of the circulating water outlet.

(5) Reducing the pressure drop across the condenser to values as low as 0·1 in Hg.

Examples will illustrate many of the features outlined.

A 50 MW (40 MW, N.E.R.) turbo-alternator set operating under the following conditions :—

Steam to be condensed (40 MW) = 295,900 lb. per hour.

Vacuum = 28·25 in. Hg. at N.E.R.

Circulating water temperature = 80° F. (cooling towers, sewage effluent).

Velocity of water through condenser = 5·8 ft. per second.

Rate of heat transmission in B.Th.U.'s per square foot per °F. per hour = 500.

Heat rejected to condenser per lb. of steam = 914 B.Th.U.'s.

Steam consumption per kWh. with feed heating $= 8{\cdot}62$ lb.

From steam tables $T_s = 97°$ F.

$T_e = 96°$ F.

$T_I = 80°$ F.

T_o is arbitrarily fixed at a figure somewhat less than T_s. The depression varies from 5° to 10° for high vacua and is often much greater where conditions are easier.

Assuming 7° outlet difference, giving $T_o = 90°$ F.

$$\text{Now } \theta_m = \frac{T_o - T_I}{\log_e \dfrac{T_s - T_I}{T_s - T_o}} = \frac{90 - 80}{\log_e \dfrac{97 - 80}{97 - 90}}$$

$$= \frac{10}{\log_e \dfrac{17}{7}} = \frac{10}{0{\cdot}92} = 11° \text{ approx.}$$

The cooling surface is then found from :—

$$S = \frac{\text{W.L.}}{K_1\theta_m} = \frac{295{,}900 \times 914}{500 \times 11}$$

$$= 49{,}000 \text{ per sq. ft.}$$

The quantity of circulating water required can be estimated from Q $(T_o - T_I) =$ W.L. (See also Chapter XX.)

$$Q = \frac{295{,}900 \times 914}{(90 - 80)} \text{ lb. per hour}$$

$$= \frac{295{,}900 \times 914}{10 \times 10 \times 60}$$

$$= 45{,}000 \text{ gallons per minute.}$$

Ratio $\dfrac{\text{cooling water}}{\text{steam condensed}} = 91$ or $= 72$ approx. at M.C.R.

Steam condensed at 50 MW $= 376{,}500$ lb. per hour.

The condensation rate is $\dfrac{295{,}900}{49{,}000} = 6$ lb. per square foot.

Surface area per kW. $= \dfrac{49{,}000}{50{,}000} = 0{\cdot}98$ sq. ft.

Two circulating water pumps installed if operating as a unit.

Combined capacity of pumps working together $= 46{,}400$ gallons per minute, and each pump would have a capacity of 27,840 gallons per minute, *i.e.*, 60 per cent. of the total water.

The tube particulars are : 1 in. ex. dia. 18 S.W.G. (0·048 in.).
Material—70 copper, 29 zinc, 1 tin (Admiralty mixture).
Number of tubes, 9,350.
Length between tube plates = 20 ft.
Friction head across condenser = 9 ft.
This can be estimated from :—

$$h = \frac{L.V.^2}{170d} + \frac{N.V.^2}{40}$$

Where h = friction head in feet.
L = total length of flow through condenser in feet (length of tubes × number of flows).
V = velocity of water through tubes in feet per second.
d = bore of tube in inches.
N = number of flows or passes in condenser.

The pneumatic or pressure drop, *i.e.*, $P_E - P_C$ at N.E.R.

$$= 1{\cdot}75 - 1{\cdot}706$$
$$= 0{\cdot}044 \text{ in. Hg.}$$

Data relating to further riverside and cooling tower stations are given.

(*a*) Riverside.
Output of turbo-alternator = 30 MW (M.C.R.)
24 MW (N.E.R.)
Steam to be condensed (30 MW) = 238,000 lb. per hour.
Vacuum = 29 in. Hg. with C.W. at 55° F. (24 MW) (Baro. 30 in. Hg).
,, = 28·8 ,, ,, ,, ,, 60° F. ,, ,, ,,
Circulating water = 20,000 gallons per minute.
Cooling surface = 25,000 sq. ft.
Number of tubes = 7,180.
Tubes—Admiralty mixture (70 : 29 : 1) ¾ in. ex. dia. 18 S.W.G.
Undivided condenser with two passes.

The condensation rate is $\frac{238{,}000}{25{,}000} = 9{\cdot}5$ lb. per sq. ft.

Surface area per kW. $= \frac{25{,}000}{30{,}000} = 0{\cdot}84$ sq. ft.

Two pumps—each 12,000 gallons per minute at 38 ft. head (two pumps running in parallel).

(*b*) Cooling Tower.

Load in MW at 0·8 pf.	Wt. of Steam Condensed lb. per hour	Outlet Temp. of Circulating Water °F.	Abs. press. Turbine Exhaust in. Hg.	Temp. of Condensate °F.
30	221,750	92·7	2·00	101
24	174,280	90·0	1·75	96
18	135,270	87·8	1·60	93

Circulating water . . .	27,000 gallons per minute
Inlet temperature of circulating water	80° F.
Cooling surface . . .	29,000 sq. ft.
Number of tubes . . .	6,520
Diameter of tubes . .	1 in.
Thickness of tubes . .	18 S.W.G. (0·048 in.)

Divided condenser.

Two pumps—each 17,000 gallons per minute at 61 ft. head (two pumps running in parallel).

(*c*) Riverside.

60 MW (M.C.R.) . . .	29 in. vacuum (barometer 30 in. Hg.)
Steam condensed . . .	405,000 lb. per hour (915 B.Th.U.'s per lb.) + 34,200 lb. per hour at 164° F.
Circulating water . . .	41,600 gallons per minute
Inlet temperature of circulating water	55° F.
Cooling surface . . .	54,000 sq. ft.
Number of tubes . . .	9,056
Material of tubes . . .	Admiralty mixture
Length between tube plates .	22 ft. 9 in.
Thickness of tube plates . .	$1\frac{1}{4}$ in.
Velocity of water through tubes.	5·5 ft. per second
Condenser friction . .	9·3 ft.

Two pumps each 22,000 gallons per minute at 30 ft. head.

Divided condenser with two passes.

Two extraction pumps each 750 gallons per minute at 180 ft. head.

Two air ejectors, each 100 lb. dry air per hour.

(*d*) Riverside (American).

35 MW	28 in. vacuum.
Steam condensed	280,000 lb. per hour.
Circulating water	37,500 gallons per minute.
Inlet temperature of circulating water .	80° F.
Cooling surface	33,000 sq. ft.

Two pass with a divided water box.

CONSTRUCTIONAL DETAILS

General. Condensers are nearly semi-circular when viewed from the ends. Whatever the shape, floor space and height of basement are important in the layout. The placing of the condenser immediately below the turbine is standard practice and does not effect the turbine or alternator overall dimensions.

The flow of the steam and air mixture is downwards, the steam is being condensed before the whole surface is traversed, and the condensate will be cooled below the condensation temperature.

This could be overcome by inverting the condenser, Fig. 320, so that the direction of steam flow is upwards, which is an ideal arrangement, thermodynamically. With such a layout the actual surface on which the steam is condensed may vary according to the load on the turbine, and this is quite independent of the total cooling surface in the condenser. All the condensed steam would drip back through the hottest part of the condenser instead of towards the cooler region as in the standard arrangement, and the surface remaining after all the steam is condensed would act automatically as air-cooling surface. For the highest efficiency the circulating water would then be reduced as far as possible without impairing the efficiency. The large floor space and interconnecting exhaust chamber do not make it a practical proposition. Messrs. C. A. Parsons make an inverted condenser in which the steam passes to the bottom of the condenser and heats the falling drops of condensate up to its own tempeature. Air is removed from the top of the tube nest at a point far above the water extraction branch thus ensuring air-free feed water.

Condenser design and construction varies with almost every manufacturer, and it is impossible to deal in detail with the types in use.

The next question for consideration, particularly with large units, is whether a divided or undivided condenser should be adopted (Figs. 321 and 322). Local conditions will generally be the deciding factor, the problems involved being those of circulating water and plant availability. The divided type of condenser has two water sides and one common steam side. In this way it is possible to arrange for cleaning half of the tubes whilst the other half is still in service, thus enabling the set to carry about half its normal rated output.

This form of construction although perhaps slightly more

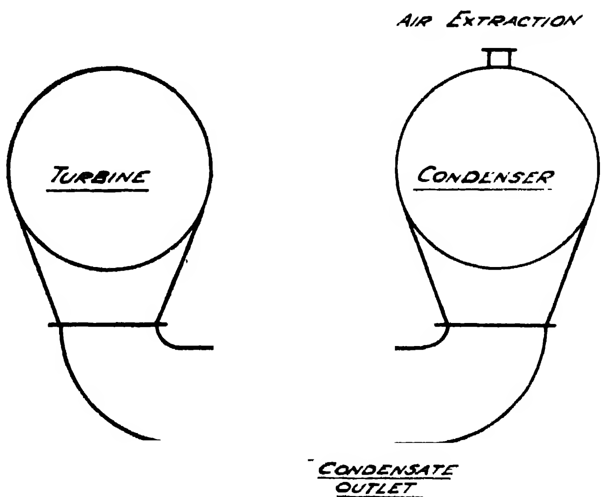


FIG. 320. Arrangement of Inverted Condenser.

expensive is adopted for both cooling tower and riverside stations. The divided condenser is essential for stations where rivers carry large quantities of leaves, wool, thread or other *débris* and waste at certain periods of the year, leaves in particular being prevalent during the autumn and early winter months. During abnormal periods the sets may be kept in service at reduced load. The influx of leaves in some small rivers is so great that the screening plant cannot cope with them, resulting in the shutting down of plant owing to shortage of screened water.

The arrangement of circulating water piping and valves is rather more expensive since each must be isolated as desired. Each half may have a separate pump, or by valve arrangement two pumps can

work in parallel and serve either half as circumstances demand. A butterfly valve at each condenser inlet is suitable, for although a leakage may be experienced the quantity passing into the isolated

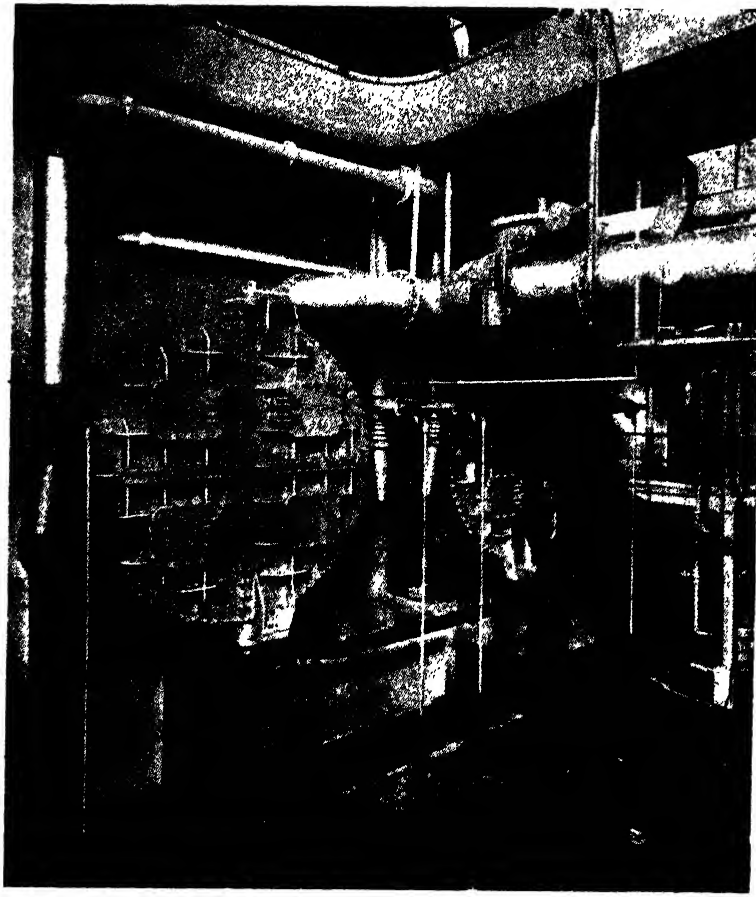


FIG. 321. Twin Surface Condenser for 75,000 kW. Set.
(Hick Hargreaves & Co. Ltd.)

half is small. It is usual to provide an isolating valve on each air suction pipe with a divided condenser.

The number of passes will vary according to the design and this no doubt has an effect on the performance, for the steam distribution is likely to be better in a two-pass than in a single-pass condenser.

Two-pass condensers are usual but three-pass types are in service. The former are commonly used for river and estuary stations and the latter for cooling tower stations. In no condenser is the flow of water strictly contraflow to the steam flow for the water flows from end to end, while the steam flows downwards and is therefore really a cross flow. The division between the two water flows may be in the vertical plane instead of the more usual arrangement in the horizontal plane. In either arrangement it is possible to arrange the coldest water to come in contact with the steam (depending on circulating water system layout) at its entry into the condenser, which results in this portion of the condenser having a much greater temperature rise.

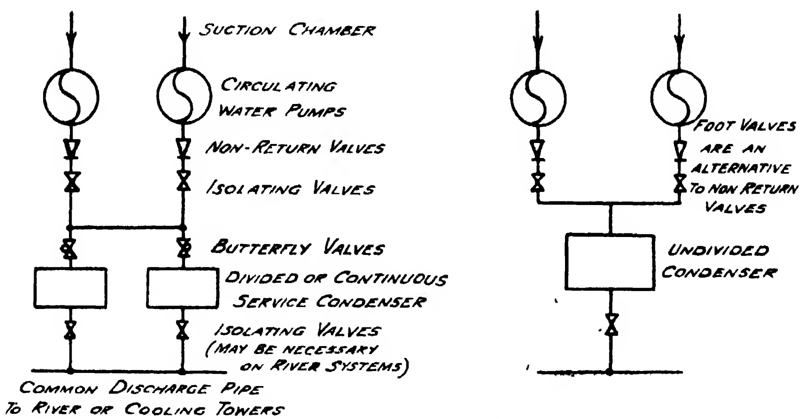


FIG. 322. Condenser Layouts.

An advantage of the vertical division is that it gives better access inside the inlet and return boxes for tube cleaning than with a horizontal division.

Metropolitan Vickers make the central flow type, the principle of which will be understood from Fig. 323. Fig. 324 shows the ordinary type of condenser.

The shell is made considerably larger than the tube-plate to provide a large volute around the nest of tubes giving the steam access to the whole periphery. To take full advantage of the entire admission of steam to the tube nest the water circulation is designed, as far as possible, on a concentric or annular flow arrangement. The air with its accompanying vapour is drawn away from the centre of the condenser which causes the steam to flow radially inwards from the periphery. The air chamber is surrounded by a

core of tubes which is supplied by the first flow or inlet water while the outer belt of tubes is supplied by the return flow circulating water. The heat transfer system is thus contraflow in principle. The length of the steam path is about half of that of the older type of condenser in which the steam traverses the entire diameter of the nest of tubes. Further, the area of steam admission is very large, being more than twice that of the earlier designs. The steam entering the tube nest over nearly the whole of the periphery reduces the velocity to a minimum, and this, in conjunction with the central air removal

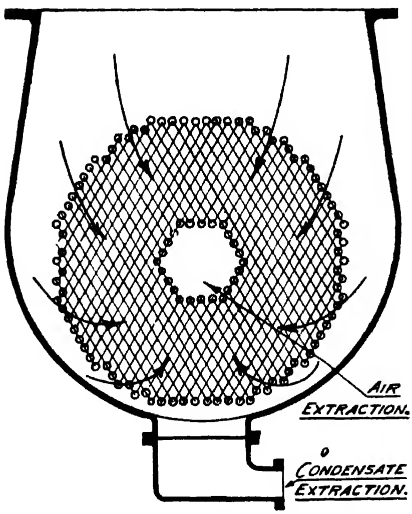


FIG. 323. Diagrammatic view showing the Steam Path in a Central Flow Surface Condenser. (Metropolitan Vickers Electrical Co. Ltd.)

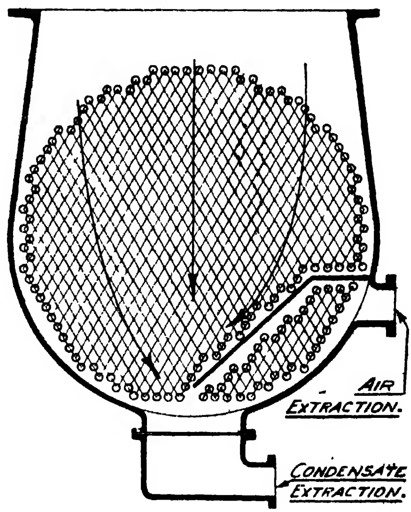


FIG. 324. Diagrammatic View showing the Steam Path in the ordinary Down-flow Type of Condenser.

which provides the shortest path, reduces the pressure drop to a minimum and so ensures the attainment of a high average range of heat transmission. By surrounding the whole of the tube nest the steam comes into intimate contact with the falling condensate and as a result the temperature of the condensate as it leaves the condenser very closely approximates to the vacuum temperature at the steam inlet to the condenser. This re-heating of the condensate makes the condenser completely re-generative.

Another feature of the central air off-take is that the maximum condensation takes place where the air concentration is least, resulting in the minimum absorption of air by the condensate, the oxygen content being reduced to a negligible value.

The chief advantages claimed for the central flow condenser are :—

(1) *Improved Rate of Heat Transmission.* The more effective use of the cooling surface enables a given performance to be attained with a smaller tube area or a better performance with a given area of cooling surface.

(2) *High Condensate Temperature.* The condensate leaves the condenser within about half a degree of the temperature of the exhaust steam, thus reducing the expenditure of heat to be provided by the boiler.

(3) *De-aeration of Condensate.* The condenser effectively reduces the oxygen content of the condensate to a negligible value and separate de-aerators are normally unnecessary.

(4) *Improved Ejector Performance.* A lighter duty is imposed on the ejectors by the condenser design enabling the size of these to be reduced with a decrease in the steam required for operation.

A special form of condenser of the vertical regenerative type has been used but is expensive and requires considerable space. The condensate outlet is arranged on the steam inlet side to ensure a condensate temperature corresponding to the temperature of the exhaust steam from the turbine. The tubes are expanded in the top tube plates but are packed in the bottom tube plates with metallic packing. The circulating water through the condenser is normally arranged to have a two-flow circuit but bye-pass and change over valves are provided which enable the flow of water to be reversed or the condenser to operate as a single-flow plant.

Side entry condensers are also possible. This design offers certain structural advantages contributing to lower cost of construction and the headroom between the turbine and condenser is reduced. The only disadvantages of this form of construction are the small additional cost of the right angle connection for the exhaust and the somewhat inderterminate but minor pressure loss between the exhaust flange and condenser inlet.

Shell. Steam turbines which have two exhaust branches may have the condensing plant designed in a single shell with twin inlet connections or with twin shells connected by a balance pipe provided the design of the turbine and its foundations do not present any difficulty. With either method the necessary cooling surface could equally well be arranged in one or two shells. The temperatures involved are so low that the connection of two inlet branches on one condenser shell does not cause any expansion difficulties and single shell condensers are now made so large in size that the provision of one shell as compared with two is not a matter of any importance. Some makers are of the opinion that a more uniform and natural flow of steam over the cooling surface can be obtained with two

separate shells resulting in a higher efficiency in air extraction. In the case of a single shell condenser with twin inlets the arrangement of the air extraction points is not so convenient as with twin shells where the air extraction connections are placed where the two shells come closest together immediately underneath the centre point of the turbine low pressure cylinder. The sub-division of the water circuit into two parts (arranged for continuous service) so that the inside of the tubes in one half can be cleaned without taking the set out of commission can be equally well arranged in single or twin shell condensers. Messrs. Richardsons, Westgarth & Co. Ltd. have made a single shell condenser for a set of 100 MW output. This unit has twin air extraction connections and double water circuits but is theoretically not designed for half-cleaning. The shell may be constructed of either cast-iron or fabricated steel plates, but the waterboxes and return end doors are usually of cast-iron, although steel plates have been used.

The end doors may be in halves and have ball-bearing hinges so that they can be opened to facilitate tube cleaning. A number of hinged inspection doors are also included.

A divided waterbox enables one half to be cleaned while the other half is in service. Waterbox stays are of bronze and steam space stays of steel bar.

The rigidity of the steel plate shells is ensured by adequate external ribs welded to the body and by internal bracing. The reduction in weight by using steel plate construction cheapens and facilitates transport. The shell should withstand any shocks imposed during transport. Riveted mild steel shells have also been used.

Supports. The condenser is arranged to bolt direct to the turbine exhaust flange, and adjustable spring supports (Fig. 325) under brackets on the shell prevent straining the exhaust flange either by weight of the condenser or by expansion of the condenser or turbine exhaust. The position of the feet is determined from consideration of stability, and the supporting springs on which the weight of the condenser is carried are proportioned to suit the loading. The supporting arrangement comprises: spring, sole plate, top keep, bottom keep, centre bolt and nuts, adjusting screws and nuts, jack bolt and trammel gauge.

After the condenser has been water tested and completely assembled, the waterbox is filled with water and the extra compression of the springs noted. The trammel gauge is then used and reference marks are impressed on the top and bottom. The mark on

the bottom keep is fixed and the position of the mark on the top keep (which must be taken from gauge) is made after spring has been compressed to working conditions. The tubes and boxes being filled with water the condenser should be set up to exhaust flange of cylinder, care being taken that no extra compression is put on the springs. An instruction plate giving the general instructions is fitted, typical wording being :—

Before water test.

Jack bolt to be screwed hard down on sole plate.

Under working conditions.

Jack bolt to be set up $\frac{1}{4}$ in. clear of sole plate.

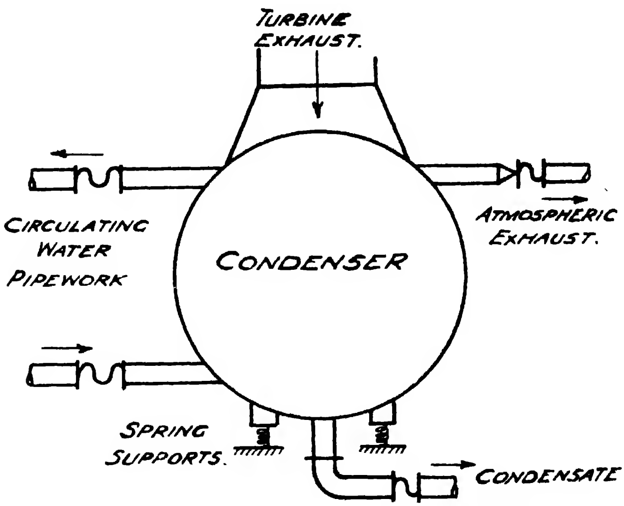


FIG. 325. Condenser Connections and Supports.

Tubes and Tube Plates. The size of tube to be used is generally chosen, not from the question of heat transfer but rather by the quality of the circulating water. Tubes of $\frac{3}{4}$ and 1 in. are usual, chiefly from a tube cleaning point of view. At the water inlet ends the tubes are expanded (Fig. 326) into the tube plate, the tube ends being expanded or belled to register with the corresponding radii on the tube plate. Care is necessary when expanding for over-expanding may cause splitting of the tubes. The tubes are annealed at the end where expanding is done and over-annealing causes brittleness and consequent splitting during the process of expanding. Splitting may also result if the tube ends protrude too far out of the

tube plate and thus permit of over-expanding. This construction minimises the turbulence in the water flow at the inlet to the tubes and eliminates erosion at this point. At the return ends the tubes are secured by ferrules screwed into the tube plate and packed with linen tape treated with tallow. Metallic packing may be used but linen packings have proved satisfactory. Accurate machining of the stuffing boxes and ferrules prevents condenser leakage.

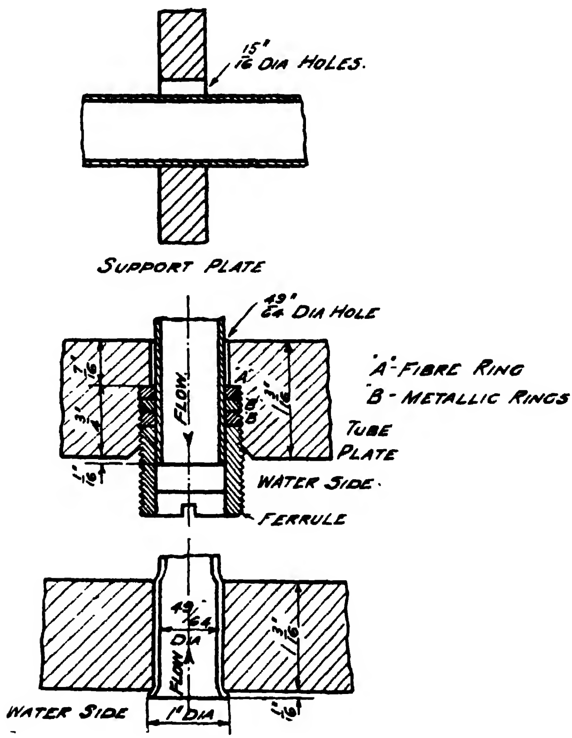


FIG. 326. Typical Condenser Tube Details.

Some condensers have the tubes expanded at both ends, the differential expansion being taken care of by an expansion piece between the body and the water box, the latter being free to move horizontally on a roller bearing.

The problem of condenser leakage was mentioned under instruments in Chapter IX, Vol. I, and full operating conditions must be reviewed when planning a layout. Condenser leakage may be due to drumming of the tubes, and such a leakage cannot always be

detected by filling the steam space with water. Failure of stay-tube joints also contributes to leakage.

Taking a cooling tower installation, the static head of water above the bottom row of tubes may be 30 to 35 ft. Adding this to the head corresponding to a vacuum of 28·4 in. Hg. a total pressure of 29·4 lb. per square inch exists between the water and steam space with greater possibility of tube leakage.

Ferrules have been used at both ends and no serious trouble has been experienced. The brass ferrules are screwed and bell-mouthed, care being taken not to compress the tubes when screwing up the packings.

Tubes are of solid drawn alloy, 70 per cent. copper, 29 per cent. zinc and 1 per cent. tin. Aluminium tubes, 70 per cent. copper, 28 per cent. nickel, 1 per cent. Fe and 1 per cent. manganese have also been used. Arsenical copper containing 0·15 to 0·75 per cent. arsenic overcomes trouble from dezincification both in fresh and tidal water. Dezincification has also taken place on cooling tower systems due to contamination of the water by chimney gases. Magnesium anodes in one side of each divided water box condenser may prove effective in retarding galvanic corrosion of tubes.

Condenser tubes may be annealed by heating for one hour at a temperature of from 250° to 300° C. during manufacture. Tubes are usually annealed by subjecting each end to a temperature of 500° C. (dull red) for two to three minutes. Each tube is water tested to a pressure of 1,250 p.s.i. The Yorkshire Copper Works Ltd., Leeds, have carried out considerable research on condenser tube manufacture and design.

Steel tubes have been used, but the results show that the heat transfer is much below that of the usual materials and the life anticipated would be very short.

Failure of condenser tubes by vibration (drumming) caused by synchronism between some natural period of vibration of the tubes and that of the turbo-alternator has been experienced. Unsupported lengths of the tubes are limited to between 5 and 6 ft. The sagging plates affording support to the tubes between the tube-plates are set slightly higher than the tube-plates so that the tubes are given a definite lift at the centre, ensuring that all water drains out of them when the condenser is shut down.

Tube failure due to vibration may be overcome by inserting corrugated " lacing tubes " wedged between rows of condenser tubes, or alternatively by driving white pine wedges between the rows.

A certain percentage of the tubes may be plugged during tests, the condensers being required to give the contract performance under these conditions. This allows a reasonable margin for abnormal circulating water conditions and dirty tubes. Reasonable margins are 5, 10 or 15 per cent. of the tubes, a great deal depending on local conditions. When such a condenser is in normal service with the tubes unplugged the performance is improved not only by reason of the increased service but also by the increased water flow resulting from the decreased friction against which the circulating water pumps operate.

Rubber and wire gauze bullets may be used for tube cleaning, and although air gunning seems to be quite suitable for the first method, water pressure appears to give better results in the latter case. Cleaning by wire brush is also possible, the brush being fixed to a long spindle which is power driven. A wire or gauze brush is very effective but rather slow, and reliable attendants are desirable.

Joints. Various materials are used for jointing some of which are :—

Exhaust flanges . .	Brass corrugated rings and compound.
Section joints . . .	Brass wire gauze, red lead and lead wire.
Body tube plates . .	,, ,, ,, ,, ,,
Doors and tube plates .	Red lead and lead wire.
Waterbox and tube plates	,, ,, ,,
Waterbox and doors .	Canvas and tallow.
Inspection doors . .	,, ,, ,,

Mountings and Fittings. Condensate-water level gauge, atmospheric exhaust valve, vacuum breaker, vacuum operated trip gear, steam and water space drains, vacuum gauge, high condensate-water alarm, stem and distance thermometer pockets are usual. A soda cock may also be included. An auto-feed control valve will be fitted if an open surge tank system is adopted. An alarm to indicate failure of condensate flow from discharge of extraction pumps may be fitted.

The atmospheric exhaust valve takes up considerable space if a 26-in. to 30-in. valve is required, 30- and 50-MW turbines. The valve should be well maintained, although it may never be called upon to operate under the conditions for which it was designed. In one case the circulating water pump failed, due to an electrical disturbance which resulted in a rapid drop in vacuum, but unfortunately the atmospheric valve failed to operate and the condenser shell fractured due to over pressure. A water sealing device is included and a water supply maintained, *viâ* a ball float chamber.

It is now the practice to include a device for gradually and automatically unloading the turbine should the vacuum fall below a predetermined figure. When this is fitted the exhaust valve can be reduced, 8 in. for a 30-MW turbine. The exhaust pipe is consequently reduced in diameter and an improved layout is possible.

The vacuum breaking valve fitted to early sets is rarely used, and can be omitted. Should the need arise for the turbine to be

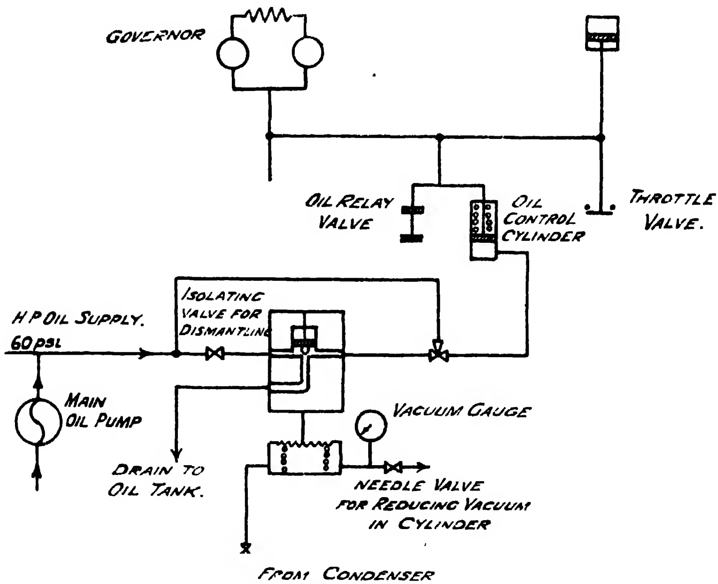


FIG. 327. Diagrammatic layout of Turbine Unloading Device.

put on atmosphere, this should be done by opening the quick start ejector isolating valve. Explosion diaphragms may be fitted in the low pressure turbine so that the usual atmospheric exhaust valve can be eliminated.

The vacuum operated trip gear works in conjunction with the gradual and automatic unloading device referred to. It consists of primary and secondary control units, the former being mounted on the governor casing thus avoiding any additional oil connection whilst the latter is fixed on the condenser.

The primary control consists of a plunger, the movement of which regulates the discharge of oil from the governor system, connected to and operated by a flexible bellows-type piston. The

piston is connected on the inside to the condenser and externally is open to atmosphere. The plunger movement is therefore controlled by the condenser pressure. The arrangement is such that if the vacuum falls to 15 in., oil is allowed to escape from the governor system thus reducing the pilot oil pressure and consequently the lift of the main valve. The secondary control protects the turbine against possible failure of the primary control. It comprises a quick-acting switch connected to a flexible bellows and mounted on the condenser. So long as the bellows are under vacuum the switch will remain open, but if the pressure in the condenser rises to 2 lb. above atmosphere the switch will close and complete a circuit which energises a solenoid on the steam end of the turbine. The plunger of the solenoid will strike the hand tripping lever and trip the main runaway valve. This switch will re-set automatically when the pressure in the condenser falls to atmosphere. The pressure-operated switch may only close an alarm circuit. Fig. 327 shows one form of unloading device.

A high-water alarm is sometimes included to give warning in the event of the condensate reaching a dangerous level. The time taken to flood a condenser if the extraction pump failed would depend on the turbine steam load. The air extraction pipe would become water-logged and the vacuum fall after about ten to fifteen minutes, in which case the atmospheric exhaust valve would probably open unless the unloading device had operated.

The waterboxes may be fitted with sets of tube-cleaning apparatus in which any of the well-known cleaning reagents such as caustic potash, caustic soda or hydrochloric acid can be used.

A 5 per cent. solution of hydrochloric acid may be circulated through a dirty condenser for some two to three hours.

Condenser leakage of very minute proportions can be ascertained by filling steam side in the usual manner and creating a vacuum of about 20 in. Hg. in the water space. Port holes provided in the water box end doors together with an electric light arranged to be raised and lowered, facilitate location of leakages. Small leakages may be tolerated on river and tower systems but must be promptly removed where sea water is used, otherwise serious contamination of the feedwater ensues. The vacuum may be obtained by the quick-start ejector. Only two fittings are required to test one tube, a solid rubber plug and another rubber plug with a hole through the middle and a thin rubber finger cover stretched over one end. The finger will collapse if there is a leak due to the partial vacuum in the condenser.

Where outlet valves are not provided on the condenser it is possible for air and oil coolers to be starved of water. The outlet legs of the condenser piping may be subject to fairly high vacuum conditions and to augment the pressure across these coolers this vacuum should be broken. Pipe connections taken from the water box side of the condenser to atmosphere *viâ* a valve prove suitable.

Failure to Maintain Vacuum. Failure of the main circulating water pump, extraction pump or air ejector, results in a fairly rapid loss of vacuum and the faulty unit is soon located. When the vacuum falls very slowly or is only slightly below the designed figure it is difficult to locate the cause. Some possible causes are :—

Air leak due to faulty sealing of turbine glands. Air leakage on condenser. Insufficient cooling water. Dirty condenser tubes. Air leak due to faulty sealing of extraction pump glands. Faulty operation of air ejector. Faulty pipe joints. Evaporator leakage.

Some idea of the performance of condensing plant will be obtained from Table 47.

Table 47. *Condensing Plant Performance*

Reading No	River Circulating Water			Condenser		Condensate Temp.	Remarks
	Inlet °F.	Outlet °F.	Rise °F.	Abs Press in. Hg.	Inlet Steam Temp.		
1	62	73	11	1·00	79	76	Very good performance.
2	,,	,,	,,	1·51	92	89	Dirty tubes.
3	,,	,,	,,	1·51	92	76	Defective air ejector or excessive air leaks.
4	,,	,,	,,	1·93	100	84	Defective air ejector and dirty tubes.
5	,,	86	24	1·42	90	86	Insufficient circulating water.

Speaking generally, the information given in Table 47 indicates :—

(1) Good performance is shown by the rise being moderate and the temperatures of the outlet water, inlet steam and condensate all being close together.

(2) Dirty condenser tubes are indicated by a wide difference between the outlet circulating water and inlet steam temperatures while the condensate temperature is high and close to that of the inlet steam.

(3) Defective air ejector (vacuum pump) or serious air leakage (both give the same result) is shown by wide difference between inlet steam and con-

densate temperatures while those of the outlet circulating water and condensate remain close.

(4) Defective air ejector or serious air leakage in combination with dirty tubes are indicated by the temperatures of the outlet circulating water, inlet steam and condensate being fairly wide apart.

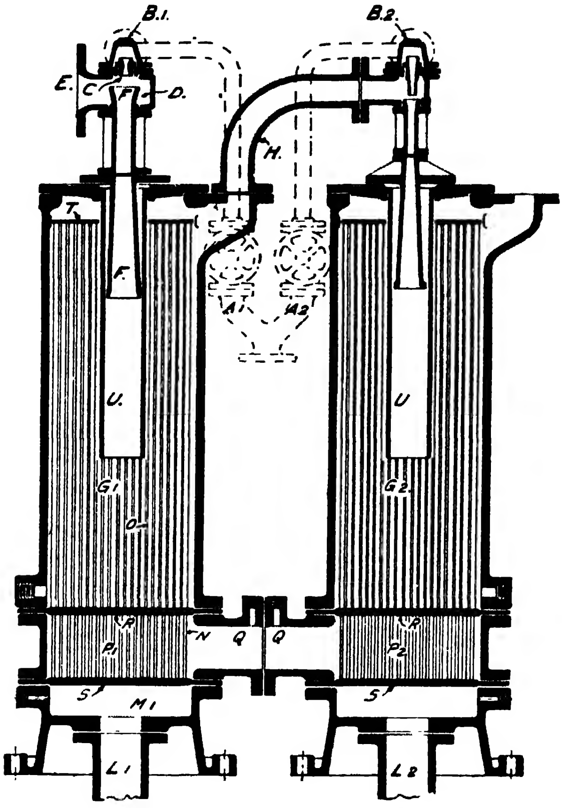


Fig. 328. Section through a typical Two-stage Ejector with Surface Coolers. (Metropolitan Vickers Electrical Co. Ltd.)

Air Ejectors. The steam-operated air ejector is simple and robust, has no moving parts, can be easily incorporated in the feed system and occupies a small space. Further, it is stable over a wide range of steam pressures, contact between air and cooling condensate is eliminated and appreciable economy results from absorption by the condensate of the latent heat of the ejector operating steam. Motor-driven ejectors are rarely used, although in

some of the 1,500 p.s.i. 1,050° F. stations Le Blanc rotary air pumps are installed to reduce the cost of small-bore piping required by steam air ejectors. In large reheat plants mechanical type dry vacuum pumps are used, one pump per set with a common spare for each pair of sets. The motor-driven vacuum pumps are chosen to eliminate high-pressure piping, valves, and associated equipment, reduce make-up and also take care of starting the boiler and set with a minimum of 50 p.s.i. The motor-driven vacuum pumps are excellent for "hogging" because of their high capacity at low vacuums.

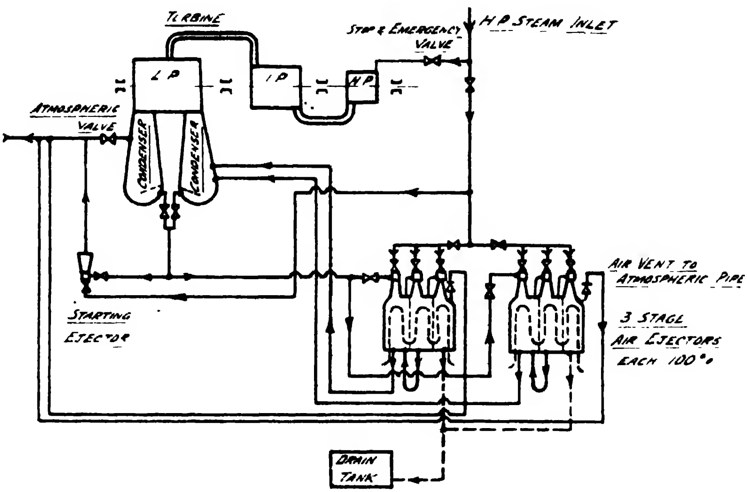


FIG. 329. Air Ejector Connections. (English Electric Co. Ltd.)

Leaks between stages are sometimes experienced which cause a slight drop in vacuum. The principle of operation lies in the projection of a jet of steam at high velocity through an air chamber wherein the air and incondensable gases are entrained by the steam, the kinetic energy of the mixture becoming transformed during compression into potential energy sufficient to discharge the mixture against a pressure higher than that in the entraining chamber. The work of compression is carried out in two or three stages to obtain greater efficiency and for the same reason surface type coolers are placed between the stages and after the last stage. The steam and vapour may be arranged for condensing either on the outside or the inside of the tubes. The steam is expanded in convergent—divergent nozzles and delivered at high velocity into

convergent—divergent diffuser tubes. The wave formation of the steam issuing from these nozzles gradually dies out as the steam passes through the diffuser tube.

A section through a typical two-stage ejector with surface coolers is given in Fig. 328. Steam is supplied through valves A_1 and A_2 to the boxes B_1 and B_2. Air and vapour from the condenser enter the first stage ejector at E and are entrained in the mixing chamber D by a jet of steam coming through the nozzle C. The mixture of air and steam is compressed in the diffuser F and discharged into the first stage cooler G_1, where the steam is condensed. The air and incondensable gases pass through the pipe H to the second stage ejector, where they are further compressed and discharged to atmosphere. Condensate from the main condenser enters the lower waterbox M_1 through the pipe L_1 and after passing through the two coolers leaves through the pipe L_2. The air suction pipes from the main condenser should always rise to the ejector.

The difficulty of ascertaining the quantity of air entering a condenser often results in the air ejector being of greater capacity than is necessary, but even with a sure knowledge of the conditions a margin of safety is advisable.

Joints under vacuum should be well-made and the complete assembly should allow for any expansion.

Formulæ which may be used is :—

$$\text{Air leakage} = \left(3 + \frac{5S}{10{,}000}\right) \text{lb. of air per hour.}$$

$$\text{or} = \frac{\text{lb. of steam per hour}}{2{,}000} + 3$$

An allowance of 5 lb. to 8 lb. per 10,000 lb. of steam is usually made. The effect of condenser pressure drop on ejector duty is considerable for as the drop increases the weight of the mixture to be handled increases very rapidly. Further, an ejector is a volume displacement machine and the total volume of the mixture to be handled depends on an absolute pressure lower than the vacuum at the condenser inlet by the amount of the pressure drop. If one condenser has a pressure drop of 0·5 in. " A " and another a drop of 0·1 in. " B " where both maintain a vacuum of 28·5 in. at their inlets, in the former case the air pump has to extract air at a vacuum of 29 in. or an absolute pressure of 1 in. Hg.; whereas in the second case the air pump deals with the air at 28·6 in. Hg. or an absolute pressure of 1·4 in. Hg. Thus in the former case the air pump has to

displace a volume of air 40 per cent. greater than in the second case. In the condenser having a pressure drop of 0·1 in. the total weight of the mixture would be about 2 lb. for each pound of air. If

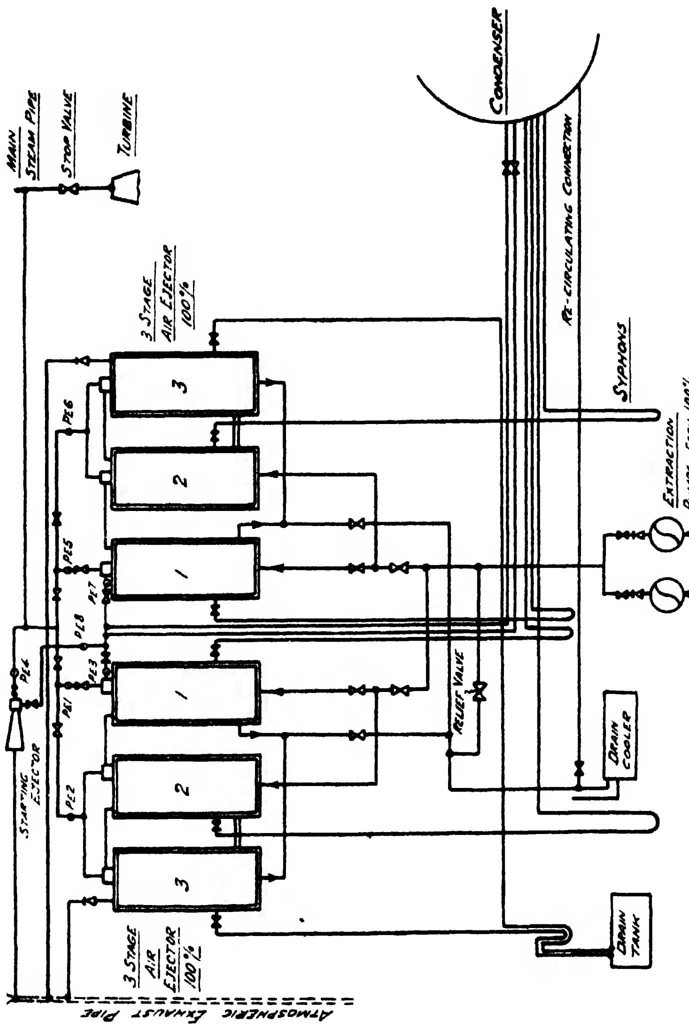


FIG. 330. Diagrammatic Layout of Air Ejectors. (Metropolitan Vickers Electrical Co. Ltd.)

the pressure drop is 0·5 in. the proportion of vapour is largely increased, resulting in the ejector having to deal with a total weight of mixture of 5·55 lb. for each pound of air. Not only has the ejector in this instance to deal with a greatly increased weight of mixture but

it has also to maintain a lower absolute pressure resulting in an increased steam consumption.

This data may be summarised as follows :—

		A	B
Pressure drop	in. Hg.	0·5	– 0·1
Total pressure (30–28·5)	in. Hg.	1·5	– 1·5
Pressure at air ejector suction (1·5–0·5) and (1·5–0·1)	in. Hg.	1·0	– 1·4
Temperature at air ejector suction	°F.	75	– 76
Vapour pressure corresponding to temperature	in. Hg.	0·88	– 0·88
Partial air pressure	in. Hg.	0·12	– 0·52
Weight of vapour/lb. of dry air	lb./lb.	4·55	– 1·05
Total wt. of mixture at air ejector suction	lb.	5·55	– 2·05

$$\text{Wt. of vapour/lb. of dry air} = 0{\cdot}62\ \frac{\text{vapour pressure}}{\text{partial air pressure}}.$$

A circulating water inlet temperature of 70° F. with the mixture at the outlet assumed to be air saturated at a temperature of 5° F. above the inlet water is taken. Figs. 329 and 330 show typical ejector installations.

Some installations have duplicate three-stage air ejectors for each large turbine and a further booster or quick start ejector to

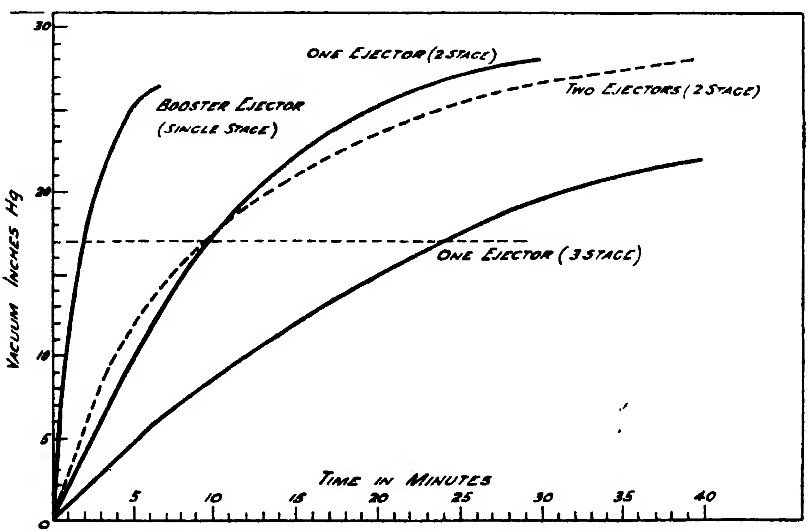


FIG. 331. Time taken to create Vacuum with Different Types of Air Ejector.

facilitate rapid starting. One of the three-stage ejectors is for stand-by service and is sometimes arranged for circulation of the main cooling water which may be sea, river or sewage effluent. The quick start ejector does not require cooling water and it is possible to raise a vacuum of 24 in. Hg. in about three minutes. This ejector exhausts the steam to the atmospheric pipe and in some localities it has been necessary to incorporate a silencer to reduce the noise.

The air ejector is in effect an air compressor and the greater the number of stages with inter-cooling the less will be the consumption of operating steam. Fig. 331 indicates the time taken to create vacuum with different types of air ejector from which it appears that the less efficient the ejector is the shorter will be the time required to raise a given vacuum. A three-stage ejector is more efficient than a two-stage but the former takes a longer time to establish a given vacuum.

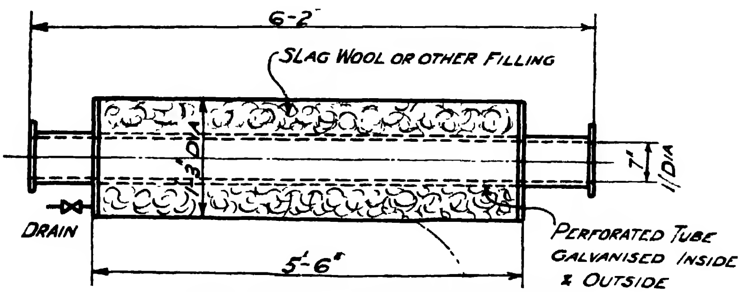


FIG. 332. Silencer for Air Ejector Booster.

Data relating to two typical air-ejector equipments are given in Table 48.

TABLE 48. *Air-ejector Data*

M.C.R. of Turbine	30 MW	50 MW
Type	Three-stage Surface Intercooler	Three-stage Surface Intercooler
Capacity of dry air, lb. per hour.	92	147
Steam required, lb. per hour .	850	1,400
Time required to establish 28 in. vac. mins.	15 with starting ejector	10 with starting ejector
Head loss at full load through cooler. Ft. . . .	10	10
Steam conditions . . .	600 lb. per sq. in.	— 850° F.

Data relating to a three-stage air ejector are :-

Steam conditions :	300 p.s.i. 750° F.
	240 p.s.i. minimum.
Steam consumption	900 lb./hr.
	or 300 lb./hr./stage.
Air duty :	dry air 96 lb./hr.
	mixture 162 lb./hr.

The features of the steam-operated air ejector are :—

Maintenance of the highest specified vacuum with perfect stability, ease of operation, low maintenance cost, starting up without auxiliary power, ease of duplication, no running parts and cost of upkeep almost negligible.

To summarise, the combined result of condenser and air ejectors should facilitate: maximum heat transmission, condensate temperature, air concentration at air pump suction, thermal efficiency of air extraction plant and minimum quantity of cooling water, pressure drop through steam space of condenser, and air pump power.

The steam ejector air pump is probably the most reliable of all auxiliaries but this does not imply that it is entirely trouble-free. This air ejector owes much of its popularity to its reliability as a high vacuum producer, together with the fact that the repairs and maintenance charges are almost negligible. Troubles sometimes experienced are, choking of steam strainer, if one is fitted, choking of drain pipes and jets.

In residential areas complaints have sometimes been made due to the high pitched note emitted by the starting ejector, and to overcome this trouble a silencer (Fig. 332) can be fitted.

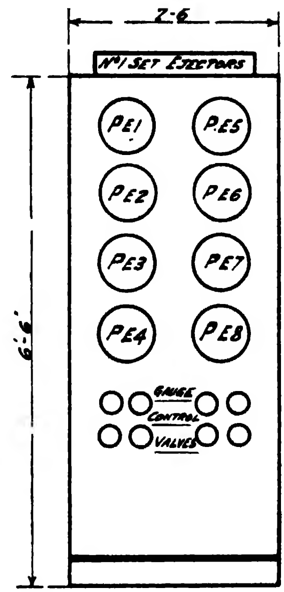


FIG. 333. Ejector Gauge Board.

P.E1—Steam to First Stage Ejector.
P.E2—Steam to Second and Third Stage Ejectors.
P.E3—Ejector Air Inlet.
P.E4—Steam to Starting Ejector.
P.E5—Steam to First Stage Ejector.
P.E6—Steam to Second and Third Stage Ejectors.
P.E7—Ejector Air Inlet.
P.E8—Starting Ejector Air Suction.

The ejectors can be controlled from a gauge board as shown in Fig. 333.

Extraction Pumps. General practice appears to favour the installation of two 100 per cent. duty pumps, one normally being in service with the other stand-by. In some installations each condenser is provided with two pumps, each of the pumps being designed to deal with the condensate corresponding to a little more than half the full load steam consumption of the set. Normally, both the pumps are in operation.

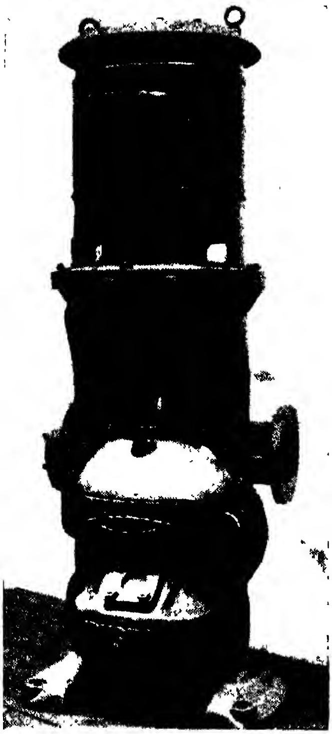


Fig. 334. Vertical Extraction Pump.

Vertical and horizontal pumps may be used, each having specific advantages. The former occupy less space and may be placed in situations where flooding is possible since the motor is well clear (Fig. 334). They are also suitable for restricted basement depth and can be designed to work with external heads of 150 ft. and over with a single stage. The suction may be placed at the lowest possible point, thus enabling the pump to produce the highest vacuum.

Extraction pumps should be reliable, have high stability factor and be accessible for maintenance. Single-stage pumps are more accessible and reliable than two-stage pumps but two-stage pumps are usually more stable and efficient than the single-stage type. Stability or freedom from gulping and noise is one of the major difficulties to be overcome in the design of these pumps. Impeller design, head on the impeller, adequate venting of the pump suction and the correct design of inlet areas and passages require careful attention if a high stability is to be ensured. The correct relation between impeller eye and tip diameter affects the efficiency characteristic and also stability. In practice it has been found that freakish instabilities have been eliminated by modification to the venting back of the condenser. This gulping or surging may affect the operation of feed-recording instruments and give false records.

The speeds of extraction pumps are worthy of attention for

extremely low speeds at high heads result in excessive internal friction in the pumps making the efficiencies lower than they would be at a more economical speed. Some idea will be obtained from the following data :—

Speed	970—1,440
B.H.P. at pump coupling . . .	45·5—39·7
B.H.P. rating of motor . . .	52·0—44·0

The fundamental conditions for successful operation are :—

(1) Air coming in through the suction should be removed from the system as soon as possible.

(2) The ingress of air at any other point should be prevented.

(3) The suction branch should be as low as possible.

(4) The operation should be stable over the whole working range.

(5) The alignment of the pump and motor should not be affected by the expansion and contraction of the interconnecting pipework.

(6) The efficiency should be as high as practicable.

Pressure-sealed glands prevent the ingress of air and consequent aeration of the condensate at these points. Stand-by pumps may be flooded to prevent the ingress of oxygen to the condensate system. The impellers are usually of phosphor bronze or gun metal. In some cases a strainer is included in the suction pipe, and although it may appear unnecessary, it is possible to have pump trouble due to pieces of wood, etc., getting into the system during the early stages of commissioning. Fig. 335 shows typical characteristic curves.

Circulating Water Pumps. Circulating water systems were discussed in Vol. I, Chapters III and VIII, and the usual methods outlined. The pumps may be arranged on a unit system or a common bus system. In the former it is usual for two pumps to serve one turbo-alternator, the pipework and valve layout being arranged to suit either a divided or undivided condenser. With the latter system a combination of large and medium capacity pumps is general, all pumps working in parallel on a common pipe range. Careful consideration should be given to the determination of the head conditions under which the pumps are to operate and the pump designer should have all data relating to the system and the maximum variations to be met. The output of a pump delivering to a cooling tower may fall off almost twice that for one taking from and discharging to a river when the supply frequency drops due to a system disturbance. The heat in the former case brings about this difference.

As a condenser becomes dirty the friction head increases and the quantity of water delivered is reduced. This is shown by a reduction in the current taken by the pump motor. Leaky pump glands due

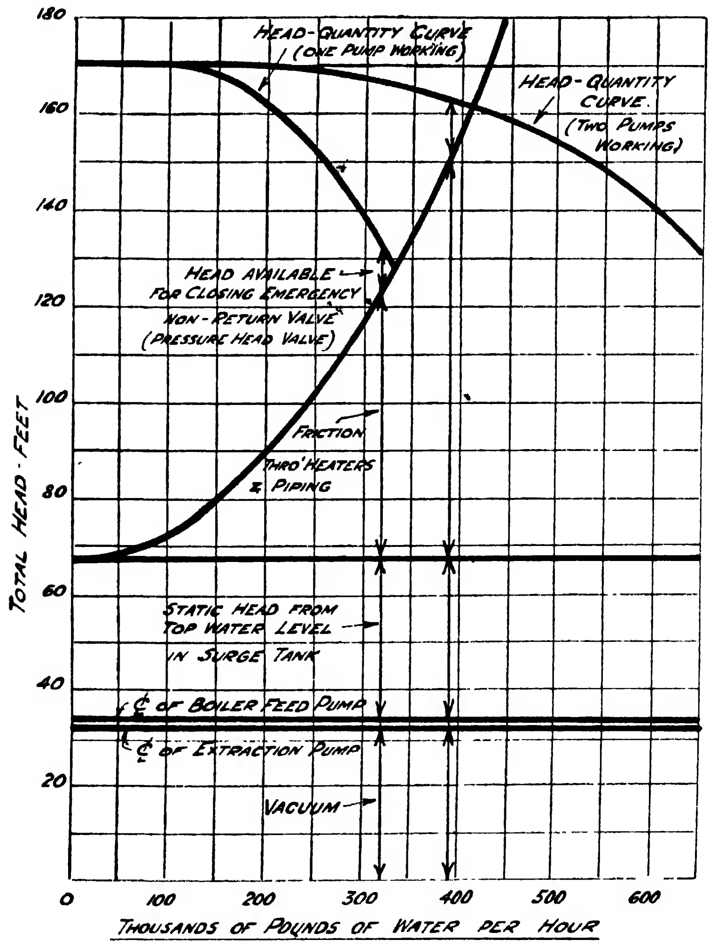


Fig. 335. Curves showing Quantity of Water which can be handled by Extraction Pumps.

to defective sealing packing will also result in a reduction in load current. If the layout involves the use of a number of pumps working in parallel, this should be stated in the specification, even though only one pump is to be installed in the early scheme. This is very important with centrifugal pumps since the total head

(suction plus delivery) varies with the quantity delivered, the manner in which this takes place being known as the pressure-

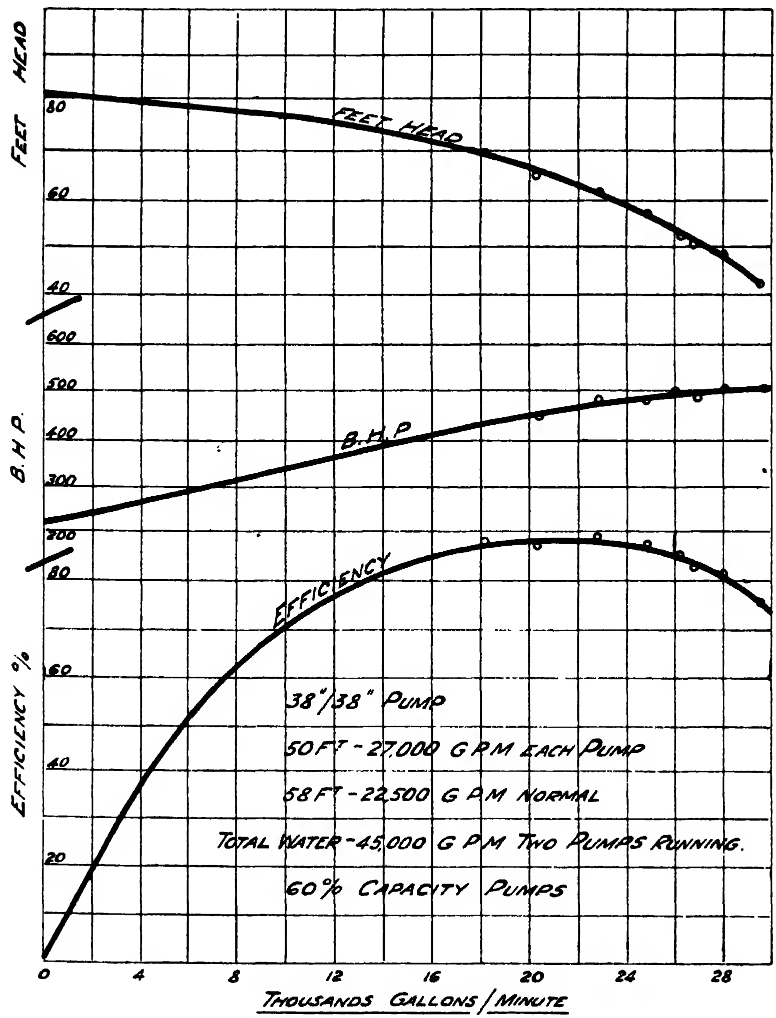


FIG. 336. Typical Circulating Water Pump Charactéristic Curves.

capacity characteristic of the pump (Fig. 336). Pumps for parallel operation must be designed so that the pressure falls continuously with increasing quantity and in this way troubles met with in the normal type of centrifugal pump are eliminated.

The estimation of the correct total head or delivery pressure is important. If the head is under-estimated, which can easily occur on difficult pipe runs, etc., the desired quantity of water will not be delivered, whilst on the other hand, with excess head it will be necessary to throttle the discharge. This procedure reduces the quantity and also the power required but the power consumption is higher than if the pump had been designed for the correct head.

The maximum head with the outlet valve closed should not impose too great a pressure on the pipe lines. Excess head may result in serious pump erosion troubles if unthrottled, and leads to continuous wastage of power if throttling is necessary. In some cases the pumps are designed to be suitable for small and large impellers, the latter being fitted when the total head has increased due to the installation of further plant. Throttling on the suction side is undesirable as erosion is set up.

Vertical or horizontal pumps may be used, and although the latter occupy greater building space and will nearly always require priming, they have advantages. All bearings are accessible and away from drip water, while split casings facilitate inspection of the impeller.

Axial flow pumps have been used and have the advantages of occupying very little space and are suitable for wide ranges of operating heads and capacities. The adjustable blade, propeller-type pumps have an advantage over the fixed-blade type in that there is a considerable saving of power especially where there are wide ranges of operating conditions (15/50 ft. head and 20/100 per cent. capacity). It consists essentially of a multiple-bladed screw rotor, normally running between fixed guide vanes of complementary design in a short section of the water pipe.

The priming of horizontal pumps can be arranged by including small steam ejectors or alternatively making use of the main turbine booster ejector. The latter arrangement is quite convenient if the pumps are near the turbines and requires an isolating valve and sight glass on each pump casing.

In laying out the pumps attention should be paid to the positions of the suction pipes. This is most essential where inlets have to be placed in culverts or restricted chambers.

It may be thought that by recessing a culvert the water flow is improved but unless the suction inlet (usually fitted with a large bell mouth) is correctly placed trouble will be experienced due to restricted water entrance to the mouth. This has been responsible for making holes in impellers, possibly due to unequal distribu-

tion of water to the suction pipe and abnormal resistance. This condition may exist if on fitting a gauge a relatively high suction is observed, in comparison to the water level obtaining.

Such a condition may be aggravated by the water used, *e.g.*, sewage or other effluent. The speed of the pumps also bears some relation to the trouble mentioned and it would appear that for very large pumps a speed of 590 r.p.m. should not be exceeded unless the conditions after thorough investigation justify a further increase. Cavitation troubles have been experienced on 400 H.P. pumps working at high speeds. Cavitation is the term used to describe the effect of low absolute pressures causing water vapour cavities to form in the mass of the water. The resultant collapse of these cavities in regions of high pressure is to cause a crackling noise under certain working conditions. Obstructions in the vicinity of suction pipes should be avoided to allow free and unobstructed flow to the pumps. Supporting arrangements have been responsible for uneven wear on foot-valve pins due to restriction of water flow. Where foot-valves are fitted the two-clack is quite suitable and is not so liable to give trouble as the multi-clack type. Inspection doors may be fitted, and if the water is screened strainers are unnecessary. Pumps having a common suction pipe may not share the load correctly and a culvert or chamber appear to be preferable. The pumps and motors should be placed on a good concrete foundation or on a specially stiffened steelwork structure if vibration is to be minimised. Care must be taken during erection not to pull the pump out of alignment when fitting the suction and discharge pipes.

The impellers may be of phosphor bronze, gun-metal, stainless steel, or cast iron. Where sewage effluent is used the steel pump shafts may be sheathed with gun-metal. Impeller trouble has been experienced at certain estuary stations where salt water and sand is circulated through the condensers on rising tides and fresh water and mud on falling tides. As the power stations were at the heads of busy ports the river water was continuously agitated, thus the maximum volume of sand and solids was kept in suspension. Owing to the tidal and siphon effect on suction head, cavitation erosion was experienced with the result that the impeller vanes collapsed due to puncturing before the periphery had wasted, due to corrosion —erosion effect. Cavitation was considerably reduced by fitting a Servo motor operated hydraulic coupling which allowed the pump to take advantage of any siphonic assistance. The impellers

were of nickel iron and meehanite (cast iron) but failure occurred after some 14,000 and 8,000 hours respectively. One was replaced by a manganese bronze and the other by an aluminium bronze impeller, but the latter gave better service. Data and formulæ required for estimating head conditions on circulating pumps are given :—

$$\text{Loss of head} = K\frac{V^2}{2g};\ \frac{V^2}{2g} = \text{velocity head.}$$

	K
Bends	0·35– 0·8
Tees	0·5 – 1·5
Valves open	0·1 – 0·2
Valves half open	2·0 – 3·0
Non-return valve	1·5 – 2·5
Foot valve	1·5 – 3·0
Venturi meters	3·0 –12·0

$$\text{For straight pipe—loss of head} = \frac{0{\cdot}006\,LV^2}{d}\ \text{ft.}$$

Where L = Length of pipe in feet.
V = Velocity of water in feet per second.
d = Bore of pipe in inches.

$$V = \frac{0{\cdot}0082Q}{d^2},\ \text{where Q = quantity of water flowing in gallons per hour.}$$

$$\text{or } V = \frac{Q}{2{\cdot}04d^2},\quad \text{where Q = gallons per minute.}$$

Fig. 337 shows effect of friction through a divided condenser.

Assuming 20,000 G.P.M. are required for a 30 MW turbo-alternator this could be provided by installing either one large pump or two half-capacity pumps. The general practice is to install two 60 per cent. pumps if they work in parallel and serve one set.

Total pipework friction	15·0 ft.
Condenser tube friction and box losses	9·0 ,,
Total static lift from min. water level	16·0 ,,
Total head	40·0 ,,

If one pump is to be used

$$\text{the B.H.P. reqd. at pump spindle} = \frac{Q \times H}{33{,}000} \times \frac{100}{e}\ (e = \text{efficiency})$$

$$= \frac{20{,}000 \times 10 \times 40}{33{,}000} \times \frac{100}{80}$$

$$= 300$$

If two 60 per cent. pumps are used the

$$\text{B.H.P. of each} = \frac{20{,}000 \times 10 \times 40}{33{,}000} \times \frac{100}{80} \times \frac{60}{100}$$
$$= 180$$

A 200 B.H.P. motor for each pump would be suitable. The advantages of two smaller pumps are that light loads can be handled more economically and failure of one pump does not cause complete

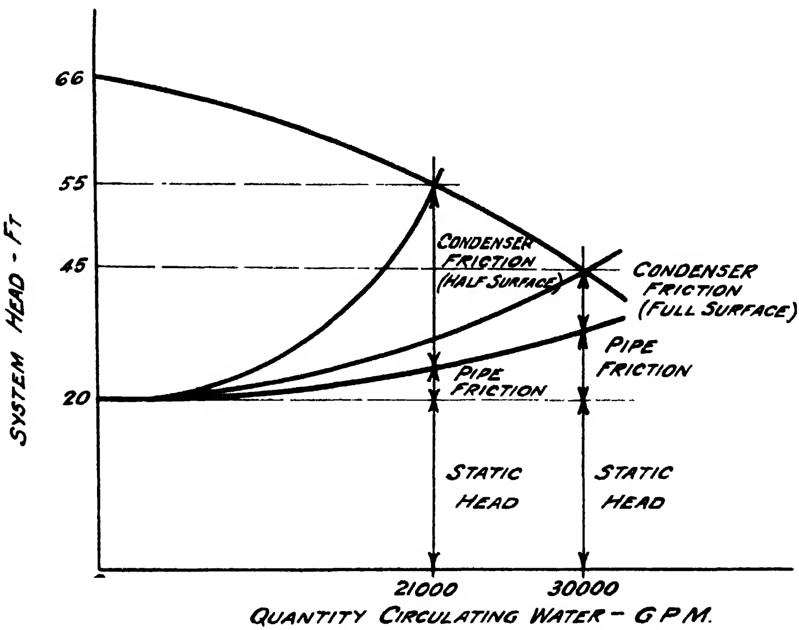


FIG. 337. Circulating Water pumped through Divided Condenser.

loss of a set. When a pump impeller is fully submerged at all water levels or tides and the discharge is similarly situated so that this water circuit is completely closed to atmosphere, use may be made of the siphonic action. With the utilisation of the siphonic principle the head on a pump is merely that required to overcome the friction of the condenser and piping.

Economic Vacuum Control. This has been tried and appears to be justifiable where the circulating water pumps for each set can be controlled independently. The system operates with thermionic valves, the grids of which are controlled by the resultant current of two C.T.s., one in the alternator cable and the other in the pump cable. The valves control a high frequency variable speed eddy

current coupling on the pump which gives a wide range of speed to suit almost any operating conditions. Such a method of control is not readily adaptable to common 'bus water systems, but is particularly suited to unit systems where each turbo-alternator has its own pump(s).

CHAPTER XI

FEED HEATING AND WATER TREATMENT PLANTS

In Vol. I, Table 1, it was seen that overall station thermal efficiencies have risen from 8 per cent. to the present-day figure of 30 per cent. This increase of over 300 per cent. is to a large extent due to the adoption of high steam pressures and temperatures, low back pressures and in some cases reheating—all giving rise to an increased heat drop. Improvements have been made in boiler and turbine efficiencies whilst regenerative feed heating has also been developed. The relatively small water capacity, high-rated surface and preheated air supply of large boiler units requires a higher temperature feed water to maintain rapid evaporation and high efficiency. Back pressures have been reduced to a vacuum of 28·5 to 29·5 in. Hg. and any further increase necessitates very low temperature circulating water and a more expensive and larger condenser and turbine. Feed heating has become a necessity on large sets as the gain in overall efficiency is partially offset by the reduced condensate temperature. The efficiencies of steam plants, non-feed-heating and feed-heating cannot be compared on a basis of steam consumption alone. The only true means of comparison is by thermal efficiency or heat consumption. When steam is bled from a low-pressure stage of a turbine, an additional smaller quantity of steam is required at the stop valve and the steam consumption is therefore increased. This increase is less than the quantity tapped off, as the latter has done work in the high-pressure stages of the turbine.

Possibly one of the first attempts to utilise some form of feed-water heating was made in 1912 on a 25 MW set. The late Sir Charles Parsons installed a screen of tubes of the same size as the condenser tubes horizontally across the whole of the upper opening through which the exhaust steam had to pass before reaching the cooling tubes. The condensate was pumped through the screen tubes with the object of raising its temperature as nearly as possible to that of the exhaust steam. No steam was extracted from the turbine.

Feed System. This is the system which connects the discharge of the condenser extraction pump to the boiler feed-water inlets.

The closed feed system is almost universally adopted, although in some cases an open surge tank is used when it is necessary to provide means for automatically controlling the supply to and from the feed system. In this system the water does not come into contact with the atmosphere. Water which has been in contact with the atmosphere may contain from 5 to 9 c.c. of oxygen per litre, the quantity depending upon the temperature of the water; the lower the temperature the higher the dissolved oxygen present. The condensate from the condenser will usually contain some 0·05 c.c. per litre. Aerated feed water is detrimental to condenser performance and causes damage to the boiler. If the rate of heat transmission in the condenser is reduced due to air blanketing of the tubes, a larger air ejector is required. The more important effect is the chemical action which takes place, causing corrosion in the boiler. Corrosion troubles were experienced to a lesser extent on old plants than on modern installations due to the formation of a protective layer of scale resulting from impure feed water.

Make-up has now been reduced to a maximum figure of about 5 per cent. of the steam load, and figures of 2 to 3 per cent. are common. This is supplied through an evaporator as distilled water, so that scale-forming water is entirely excluded from the system, making the elimination of air of primary importance. Many theories are advanced concerning the corrosion which takes place but the following is generally accepted by most engineers and chemists. A coating of iron oxide is formed if the water contains oxygen alone and there will be no further action if this is allowed to remain. Nitrogen takes no part in the chemical changes, as it is an inert gas, but should there be a minute percentage of carbon dioxide in solution in the water this acts upon the iron oxide, producing ferrous carbonates. This is dissolved in the water and reduced by the oxygen in it to iron oxide. As the carbon dioxide remains constant it is only necessary to supply free oxygen to keep the action moving. Atmospheric air contains 21 per cent. by volume of oxygen and only 0·03 per cent. by volume of carbon dioxide, but the solubility of the latter in water is nearly 30 times as great as oxygen gas. In order to remain immune from corrosion troubles, the oxygen content of the feed water should not exceed 0·1 c.c. per litre and this figure is rarely exceeded in a closed system.

Thermal Gains Resulting from Feed Heating. The aim of feed heating in the regenerative cycle is to endeavour to conserve the

latent heat which would otherwise be given to the circulating water. This is achieved by tapping or bleeding a portion of the steam from the turbine and condensing it in a feed heater, using as the cooling medium the condensate which is being returned to the boiler. The tapping point is chosen to suit the temperature of the condensate. It is necessary to select a stage in the turbine where the steam pressure has a saturation temperature some 10° to 15° F. above the required condensate temperature. Assuming the total heat content of the steam at the stop valve to be 1,350 B.Th.U.'s per lb. On passing through the turbine to the condenser the sensible heat energy is abstracted as work and the latent heat of vaporisation at the exhaust is approximately 1,000 B.Th.U.'s per lb., all of which is lost to the circulating water. Although the steam has an initial total heat of 1,350 B.Th.U.'s per lb., only 350 B.Th.U.'s perform useful work in the turbine. For the purpose of comparison the following approximate figures may be taken :—

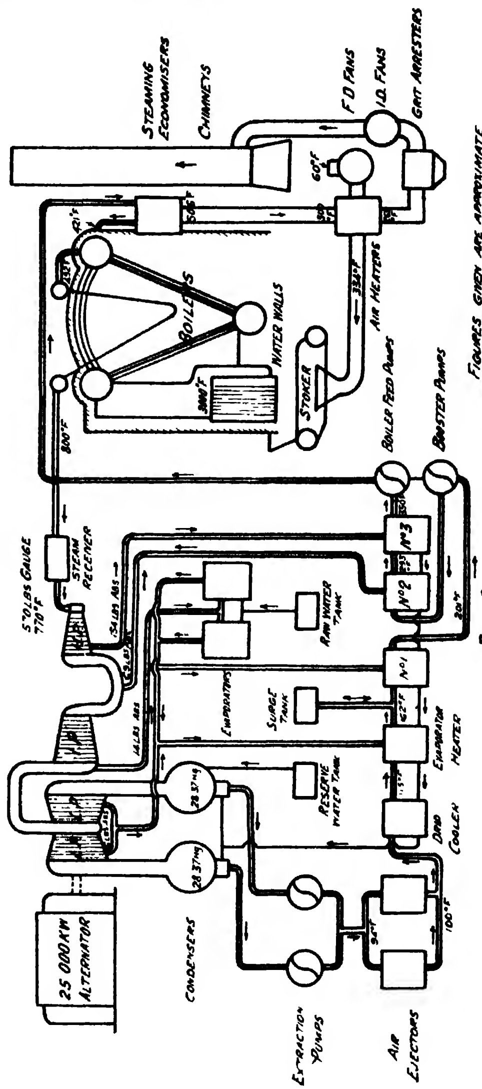


FIG. 338. Simplified Diagram of Heat System-Stoker Fired Boiler.

(1) Turbine steam consumption = 10 lb. per kW. hour (non-feed-heating).

(2) Turbine steam consumption = 10 + 5 per cent. = 10·5 lb. per kW. hour (feed-heating).

Boiler feed water (1) 88° F. (2) 200° F.

The heat consumption in (1) will be 10 (1,350 — (88 — 32)) = 12,940 B.Th.U.'s.

The heat consumption in (2) will be 10·5 (1,350 — (200 — 32)) = 12,411 B.Th.U.'s.

Overall saving = 12,940 — 12,411
= 529 B.Th.U.'s per hour.
= 4·1 per cent. approx.

Although this figure does not appear to justify the expense of installing heaters the saving in coal consumption per annum is considerable. Assuming that a 10 MW. turbine operates with a load factor of 40 per cent. and the boiler plant has an efficiency of 85 per cent., burning coal with a calorific value of 12,000 B.Th.U.'s per lb. the saving would be :—

$$\text{B.Th.U.'s saved per annum} = 529 \times 8{,}760 \times \frac{40}{100}.$$

$$\text{B.Th.U.'s per lb. of coal} = 12{,}000 \times \frac{85}{100}$$

$$\text{Total coal saved} = \frac{529 \times 8{,}760 \times 0{\cdot}40 \times 10^4}{12{,}000 \times 0{\cdot}85 \times 2{,}240}$$

$$= 810 \text{ tons per annum.}$$

It is seen that all the heat in the percentage of steam which is tapped off is retained in the system whilst the latent heat of the balance of the steam is lost to the circulating water. In other words, a percentage of the total steam performs 100 per cent. of work in the system, thereby raising the overall efficiency of the plant.

A further advantage of feed heating is that a reduction of the surface can be made in the condenser as less steam reaches it. There will also be a reduction in circulating water-pump power but an increase in boiler-feed pump power. Where there is an insufficient natural supply of circulating water, cooling towers are employed for re-cooling the water for continued service. With feed heating the steam passing to the low-pressure portion is reduced, therefore less circulating water is required for the condenser, with a corresponding decrease in the capacity and cost of the cooling towers. The output of a turbine at a particular speed is limited by the area of the exhaust annulus, and therefore by

bleeding steam from intermediate stages the output of a standard frame can be increased.

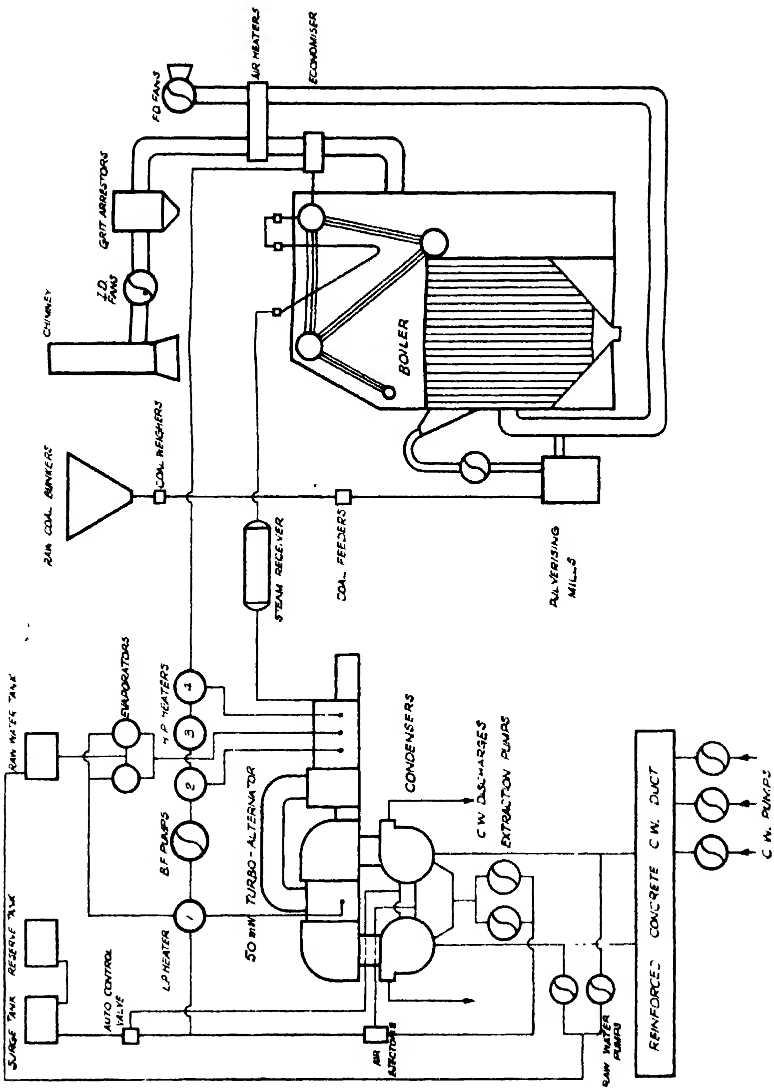


FIG. 339. Simplified Diagram of Heat System-Pulverised Fuel Boiler.

Feed-system Components. Figs. 338 to 341 give typical feed systems and show diagrammatically the various components which make up such systems.

Condenser. The condenser depression or difference between the vacuum temperature and the condensate temperature should be

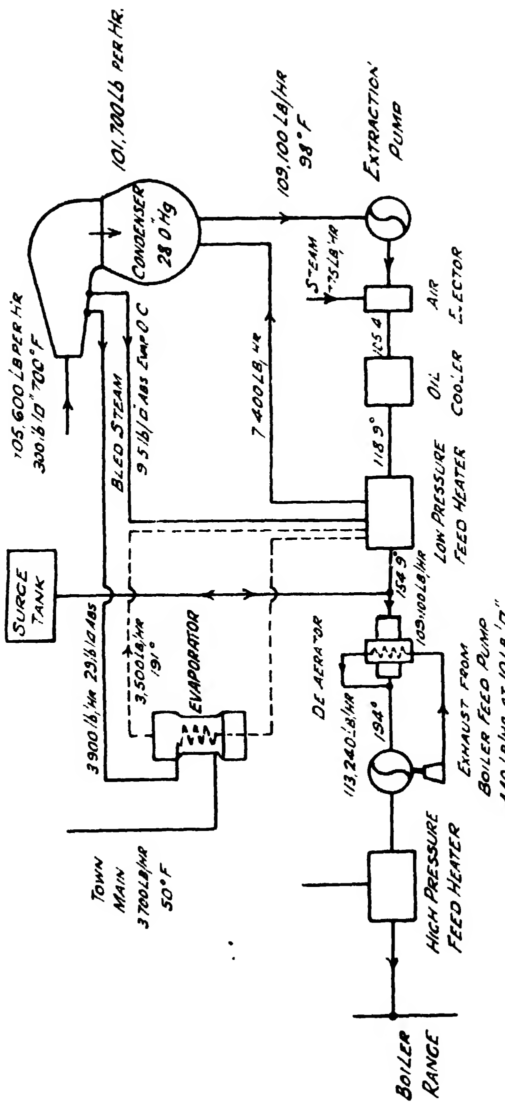


FIG. 340. Heat Diagram for 10 MW Turbo-Alternator.

kept as small as possible. Excessive air leakage tends to increase the depression and reduce the condensate temperature. It is

possible to reduce the depression to within 2° F. by providing spacious lanes through the tube nest, thereby allowing the steam

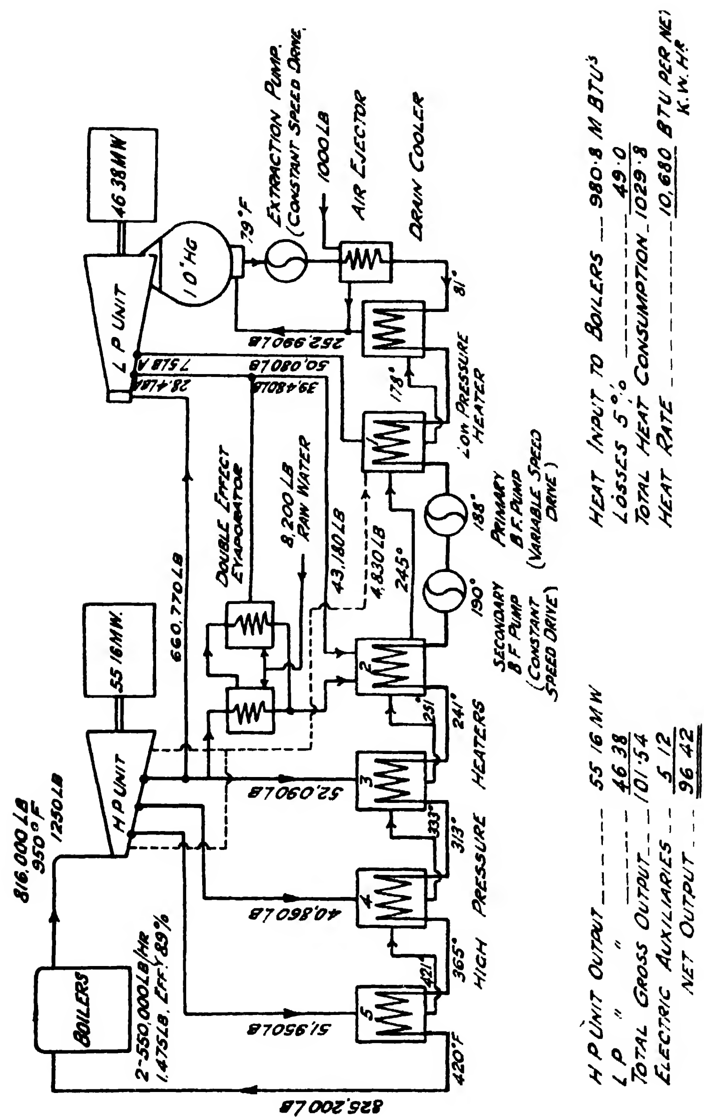


FIG. 341. 5-Stage Feed Heating System with Cross-Compounded Turbine.

access to the bottom of the condenser. Condensate temperatures have been obtained slightly higher than the temperature corresponding to the vacuum of the turbine exhaust, presumably due

to the kinetic energy of the steam entering the condenser being converted into pressure near the bottom. If steam is passed directly to the bottom of the condenser the depression may be reduced to zero. The drops of condensate falling through the steam are heated up to the steam temperature. Because of its zero depression the condenser acts as an efficient de-aerator and all make-up water should enter the system by way of the condenser.

Extraction Pumps. The condensate is extracted from the condenser by means of a centrifugal pump and delivered to the system. In the design and layout of these pumps care should be taken to ensure that the correct head of water is always maintained. The pumps have to handle warm water and in some cases it may be at boiling point. The available head of water above the eye of the first-stage impeller should not be less than 2 to 3 ft. to give satisfactory operation and to avoid drowning condenser tubes. These pumps may also be arranged to supply the cooling water for the gland steam condensers, this water being returned to the condensate system by way of the drain tank.

Air Ejectors. The condensate is now passed through the air ejector to condense the steam from the jets and so increases the temperature of the former by a few degrees. In a recent American station where the unit system (125 MW set with 885,000 lb. per hour boiler) is employed condensate is used as the cooling medium for the reciprocating dry vacuum pumps.

It is also used for the primary and tertiary air jackets of cyclone burners, the slag tapping coils and the cooling coils across the boiler access doors to protect against scale and corrosion which may result from the use of raw water. To guard against oxygen intake a closed system is employed. It has an elevated expansion tank with make-up provided by the gland water tank. Heat absorbed by the cooling water is transferred to the condensate by way of a heat exchanger and pumps provide circulation in the system. Indirect raw water cooling through a separate heat exchanger is included for the starting period.

Alternator Air Coolers. In some installations the condensate is passed through the air coolers but this necessitates greater surface area of the cooler and the heat saved does not justify such an arrangement. When air coolers are included the condensate passes through these first and then on to the air ejector. Condensate has been used for both air and oil coolers where the river water was very turbid.

Drain Coolers and Steam Traps. The heating steam drains from the heaters are led to the condenser *viâ* a cooler. In this way a large portion of sensible heat left in the water is saved, and further, it obviates the necessity of drawing hot water direct to the condenser thereby impairing its capacity for condensing steam.

The condensate passes through the cooler on to the first low-pressure heater. The drains are passed through a steam trap before entering the condenser. The function of the trap is to drain the water resulting from condensation of the steam in the heaters automatically without allowing any steam to escape. To keep the cooler full of water the drain pipe should be led upwards to the trap placed just above the top of the cooler. The water level in the trap must be balanced with water level in the heater by means of an air vent connecting the body of the trap with the top of the heater. This connection is essential, otherwise the drain cooler would be emptied into the condenser by siphonic action and the greater pressure in the heater.

Drain Pumps. The drains from the feed heaters may be returned direct to the condensate main by means of a pump. It is claimed that this method shows a small gain in heat consumption over the usual drain cooler. On light load the pressure in the heater will fall to a figure approaching condenser vacuum and under all loads the water will be at boiling point. To ensure satisfactory operation under all conditions the pump will be placed some distance below the heater. The available head of water on the suction will thus prevent cavitation in the eye of the impeller. A non-return valve should be included on the pump discharge to prevent water from the feed line flooding the heater in the event of pump failure. An inverted "U" may be introduced as a safeguard to prevent flooding of the heater should the drain pump fail unnoticed. The bled steam is returned to the feed line after the heater so that a reduction in the size of heater is possible. If a drain pump is

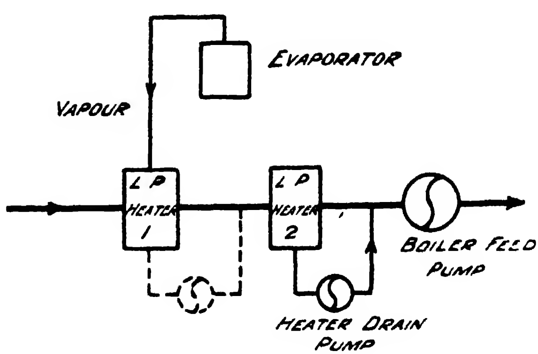


FIG. 342. Heater Drain Pump.

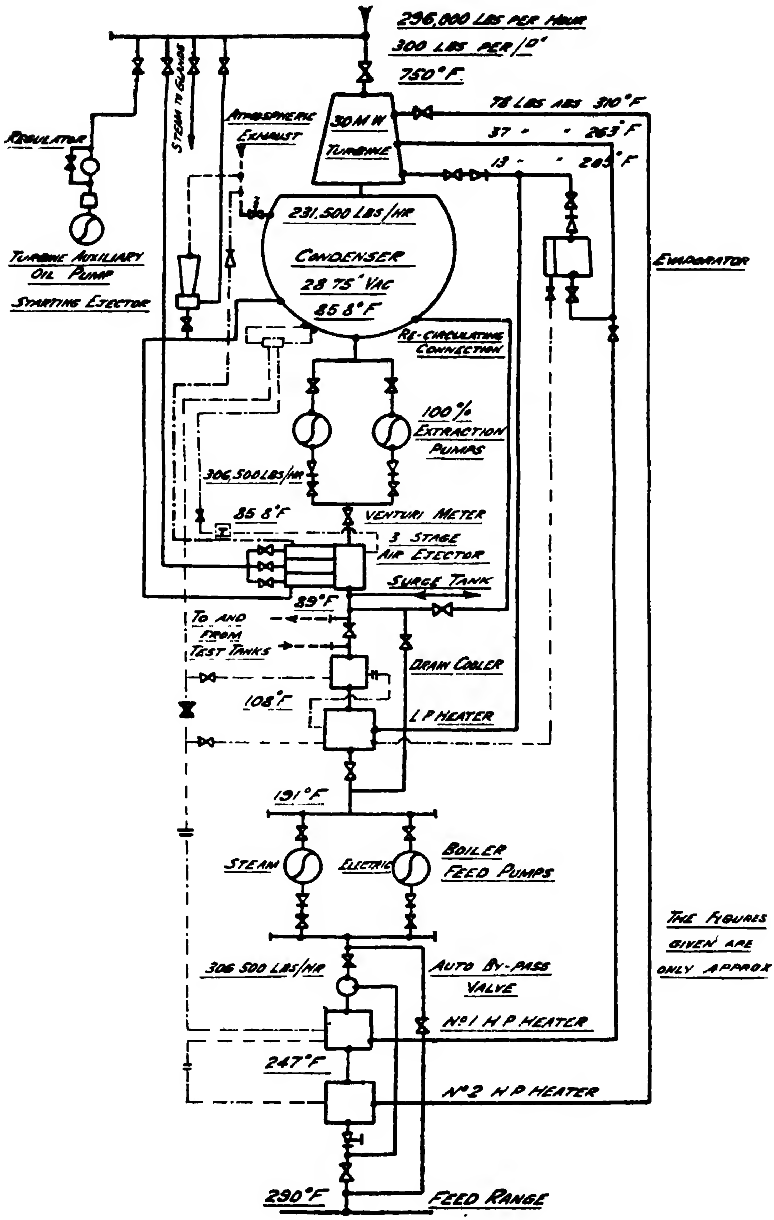


FIG. 343. Diagram of Condensate System.

fed from a low-pressure heater which takes in vapour from an evaporator it is possible to have gases carried over from the evaporator into that heater with consequent mixing in the condensate line. Such gases may lead to corrosion in the boiler tubes, etc. To overcome this it is advisable to take the drains from such a heater back to the condenser *viâ* a drain cooler. In some cases a fairly large (1 in. to 1½ in.) air or gas vent is taken from this heater to the condenser, but there is always the possibility of some gases still finding their way to the drain pump. As a further precaution the drain pump may be provided with a small vent from the suction eye of the impeller which, being placed at the lowest pressure in the pump, would release a further amount of air or gas to the condenser. Fig. 342 illustrates the heater connection to the drain pump.

Low-pressure Heaters. The condensate after leaving the drain cooler passes through the low-pressure heaters where the condensate is heated by steam taken from the turbine at suitable stages (Figs. 343 and 344).

Evaporators and Evaporator Heaters. The condensate may also be taken *viâ* evaporator heaters. The vapour from evaporators is usually taken to the low-pressure heaters.

Boiler Feed Pumps. After leaving the low-pressure heaters the condensate is taken to the suction of the feed pumps and then discharged to the high-pressure heaters. Electric and steam-driven pumps are installed, the latter acting as stand-by. The steam from the turbines is condensed in a low-pressure heater at a few pounds above atmosphere. In this way the latent heat in the live steam is returned to the feed system. The turbines exhaust to atmosphere on starting when there is insufficient condensate available from the main turbine. The feed pumps are on the inlet side of the high-pressure heaters so that they handle water at lower temperatures, a procedure which simplifies the gland-sealing and cooling arrangements.

High-pressure Heaters. The condensate now passes through the high-pressure heaters, being heated by bled steam from the turbine. It then leaves the turbine house for the last unit in the chain—the economiser.

Economiser. The economiser although incorporated in the boiler is essentially a feed heater, utilising the flue gases as the heating medium instead of bled steam. The feed water in the economiser is at a lower average temperature than the water in the boiler so that an economically justifiable rate of heat transfer is obtained. The inlet temperature of the feed water to the economiser should be kept

above 140° F. if condensation of the vapour in the flue gases is to be obviated. The moisture deposited will cause corrosion due to the presence of sulphur in the flue gases.

Automatic Control Valve. The destructive effect of an aerated feed-water supply has been noted and the necessity for maintaining

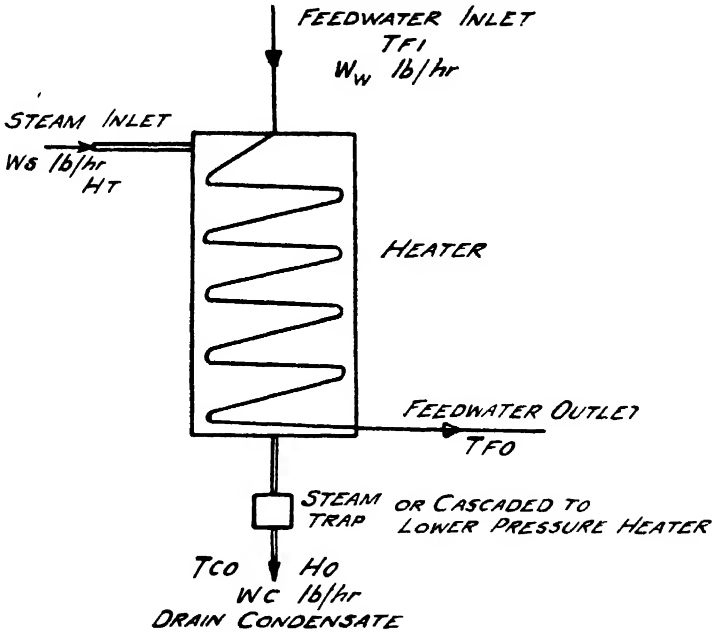


FIG. 344. Principle of Closed Feedwater Heater.

H_T = total heat ascertained from steam tables for a given pressure to be multiplied by turbine condition line factor if Bled Steam is used.

H_O = heat in condensate at outlet.
$= T_{CO} - 32.$

T_{CO} = temperature of condensate at outlet ° F.

$T_{CO} - T_{FI} = 10°$ approx.

$$W_C = \frac{W_W(T_{FO} - T_{FI})}{(H_T - H_O)}$$

an air-free system emphasised. The water repeatedly circulating in the feed system becomes de-aerated in the condenser but any make-up water will contain air in solution. A system which has a connection between the extraction pump and boiler feed pump connected to an open surge tank is not truly closed. Water in the tank becomes aerated and when the feed pump demand exceeds the supply from the extraction pump the additional water is drawn from the surge tank into the system.

By providing an automatic control valve (Figs. 345 to 347) it is possible to ensure that all additional water entering the feed system passes into the condenser for de-aeration. The valve chamber housing the operating float is connected to the condenser, thereby

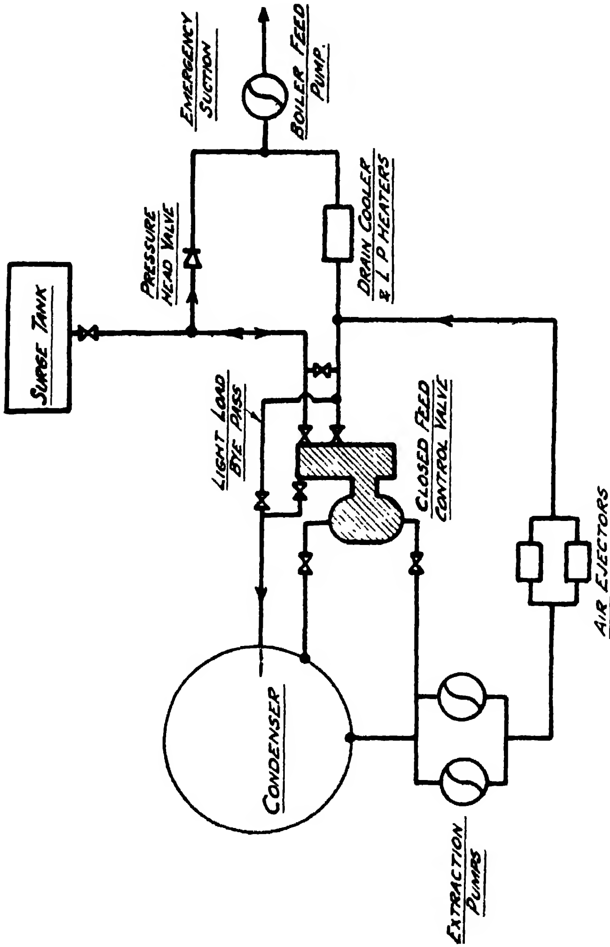


FIG. 345. Closed Feed Control Valve Connections.

maintaining a water level in the chamber on a level with that in the condenser. When a surplus of water accumulates in the condenser such as would occur with a sudden increase of load or when large quantities of make-up water are being supplied from an evaporator, it is delivered to the surge tank. If additional water is

required in the system this is led to the condenser. In mid-position both ports are closed and there is no flow of water through the valve. In the event of faulty operation the control valve is

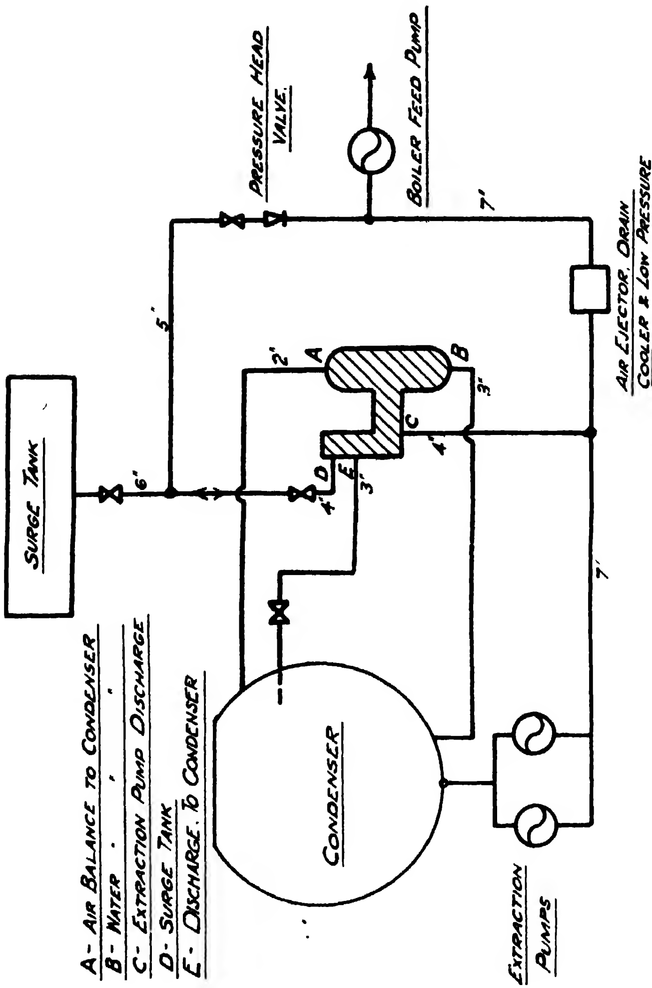


FIG. 346. Alternative Closed Feed Control Connections.

arranged for manual control or the system may be left to operate with an open surge tank until the defect is remedied. The auto-control can be locked by a hand lever and setting screw in the overflow, make-up or normal positions. In the " overflow " position the surge tank is brought in direct contact with the extraction

pump discharge and operates as a direct system. With the lever locked in the "make-up" position the surge tank is in direct contact with the condenser. In the "normal" position the valve has free movement over its full travel and flow takes place in either direction according to the demands made by the feed pump. If the hand lever is allowed free movement the pointer indicates the position of the ball float and the water level in the float chamber. When the set is shut down the isolating valve in the surge tank line is closed to prevent leakage through the valve clearances from the tank into the

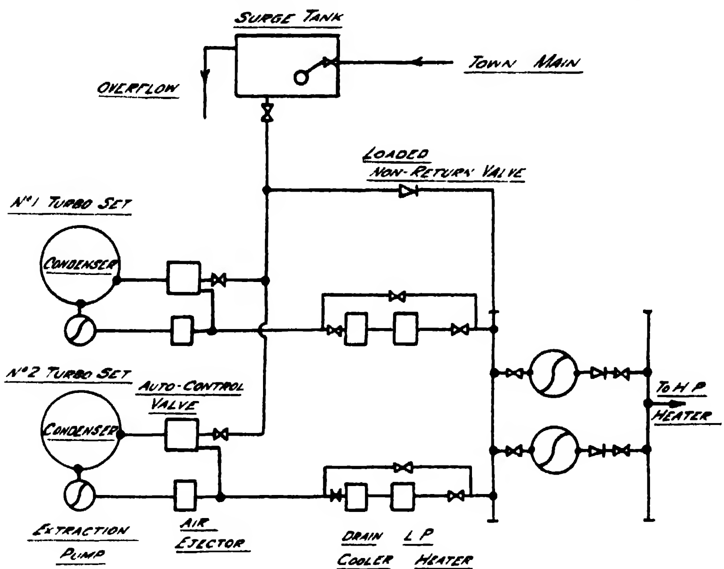


FIG. 347. Feed System using Open Surge Tank.

condenser. A minute leak in the pipe connecting condenser and valve causes the ball float to rise and fall erratically. Air at vacuum pressure occupies a large volume and bubbles produced rise to the float chamber. The loaded non-return or pressure head valve permits of a direct supply to the boiler feed pump suction should the extraction pump fail.

If the system is designed to incorporate an emergency supply to the feed pump suction an ordinary non-return valve will be allowed for. With a D.C. motor-driven extraction pump having speed control it is usually possible to raise the speed and so increase the discharge pressure to maintain the non-return valve closed against the surge tank head.

Surge Tank. The electrical load usually varies over wide limits, as for example a 30 MW set may be doing full load at one period and only 10 MW at another. These fluctuations are reflected back to the boiler and so to the feed pumps, the discharge of which is controlled by the water level in the boiler. As a result the extraction pump may not be able to deliver condensate to meet the requirements of the feed pumps and at other periods a surplus may be available. It is therefore essential to install, between these pumps, a tank of sufficient capacity to deal with the variations. Any surplus water discharged from the extraction pumps passes to the tank, or alternatively, if the demands of the feed pumps cannot be met by the extraction pump the deficit is supplied from the tank. The pressure in the condensate line should never be allowed to fall below the saturation pressure of the water, otherwise vaporisation will occur.

The condensate and feedwater system on some American plants do not include a separate surge tank, condensate surges due to varying electrical load are taken in an unusually large de-ærating condenser hot well. Storage for starting up and shutting down a unit is provided by another tank.

Multi-stage Feed Heating. If it were possible to heat the feed water up to the initial steam temperature by the use of an infinite number of heating stages the thermal efficiency of the plant would approach the theoretical maximum for saturated steam and the unit would operate on the Carnot cycle. This is impracticable, and as the number of stages increase the additional gain per stage diminishes rather rapidly. The size of economisers and air heaters employed influences the final feed temperature, but on machines of 20 MW and above it is usually 60 and 70 per cent. of the initial steam saturation temperature. Any gain resulting from feed heating will be discounted if provision is made for utilising all the heat in the flue gases.

Two examples are :—

Initial steam saturation temperature	500°	.	420° F.
Feed temperature at economiser inlet	265°	.	290° F.

The number of stages depends principally upon the capital outlay available and the degree of efficiency required. Each case should be considered on its merits and a scheme devised to meet the conditions.

As an example a four-stage may be preferred to a five-stage

system as in the latter case the design of the turbine would be more complicated with a speed of 3,000 r.p.m. and further, it may also necessitate an increase in economiser heating surface.

In practice the feed temperature is usually slightly less than that which gives maximum efficiency as the cost of the system rises with the final temperature and the gain per degree decreases rapidly

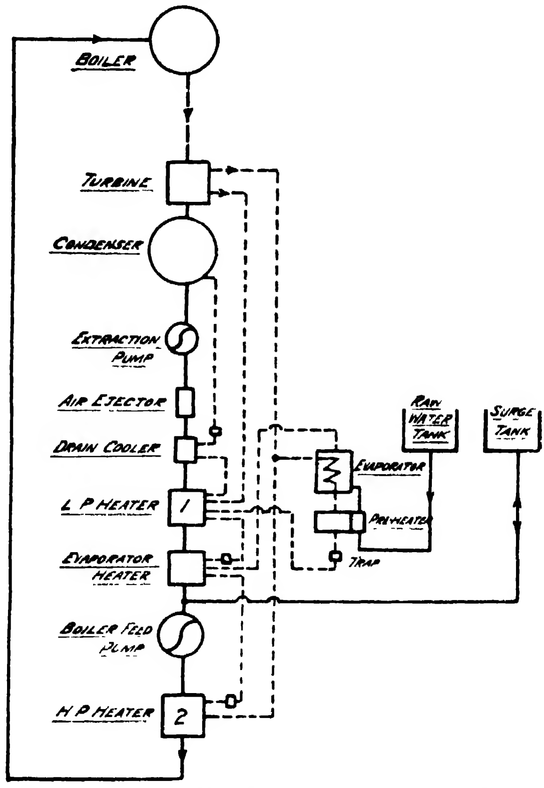


FIG. 348. Two-stage Feed System with Evaporator.

as the peak is attained. An elaborate and expensive feed-heating system will pay for itself quicker on a base-load machine with a high-load factor than on one which operates under low-load conditions or with long shut-down periods.

Two-stage System. Fig. 348 shows a typical two-stage feed system incorporating an evaporator and evaporator-heater.

It will be noted that there are three heaters in the system. The thermal gain, however, will only be equivalent to two stages of

heating as the heating steam for both the high-pressure heater and the evaporator is bled from the same stage in the turbine. The method of draining each heater into the next lower pressure one is known as "cascade." The bled steam and evaporate from the evaporator are condensed in the respective heaters and drained at saturation temperature. The heat in the higher pressure drains is

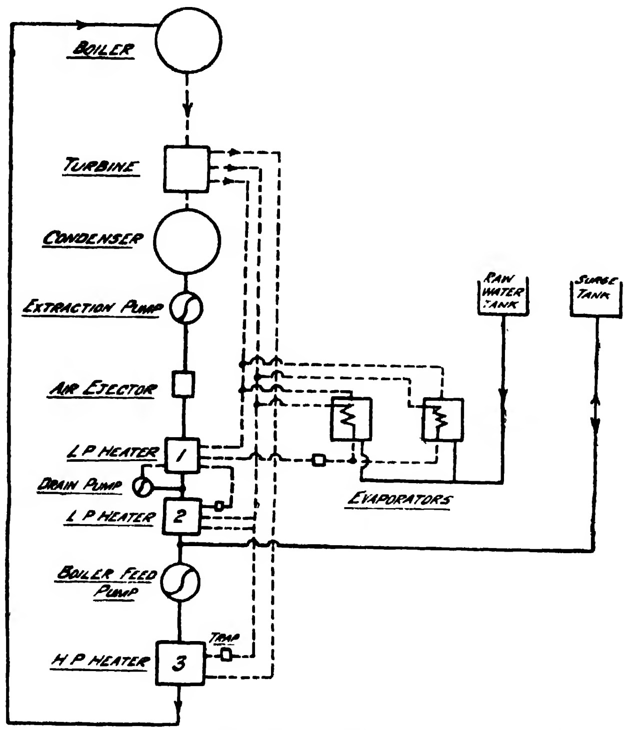


FIG. 349. Three-stage Feed System with Evaporators.

utilised in the low-pressure heater and all the drains are cooled in the drain cooler before passing to the condenser.

If desired, the drain cooler could be omitted and the low-pressure heater drains pumped into the condensate line. For cheapness, the low-pressure and evaporator heaters could be combined and so form one large unit. The quantity of steam bled from the low-pressure tap-off point need only be such as to maintain a pre-determined temperature in the boiler feed pump suction. The waterbox and the tube nest of the high-pressure heater should be designed to

withstand the discharge pressure of the feed pump, whilst the low pressure and evaporator heaters should be capable of holding the pressure from the extraction pump. The minimum cost would be reached when the maximum amount of the total heating surface is on the suction side of the feed pump. This would be obtained

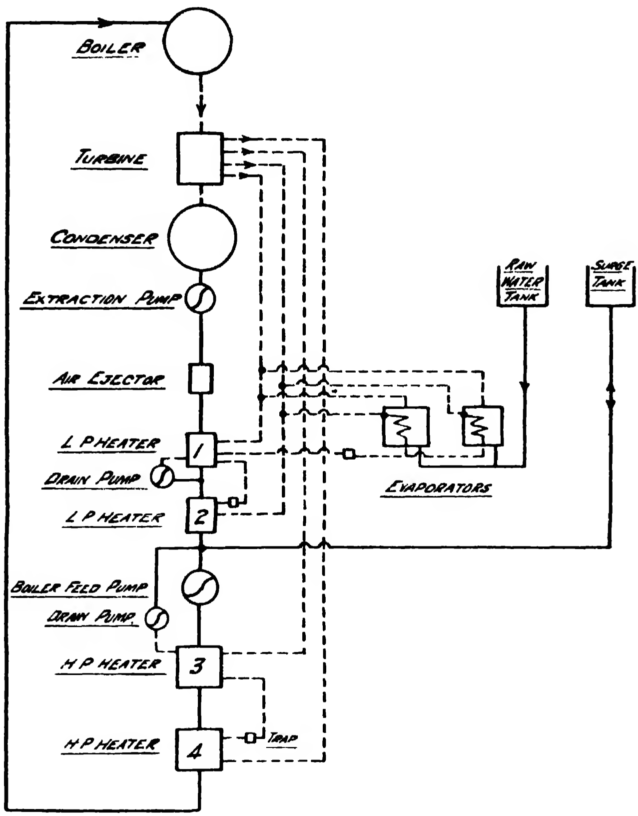


FIG. 350. Four-stage Feed System with Evaporators.

when the outlet temperature from the evaporator heater is a maximum but should not exceed 220° F. or pump troublé will be experienced. The high-pressure heater should be fitted with an automatic bye-pass valve to isolate the heater in the event of a burst tube and so maintain supply to the boiler.

Three-stage System. The system illustrated in Fig. 349 consists of two heaters on the suction side of the feed pump and one on the

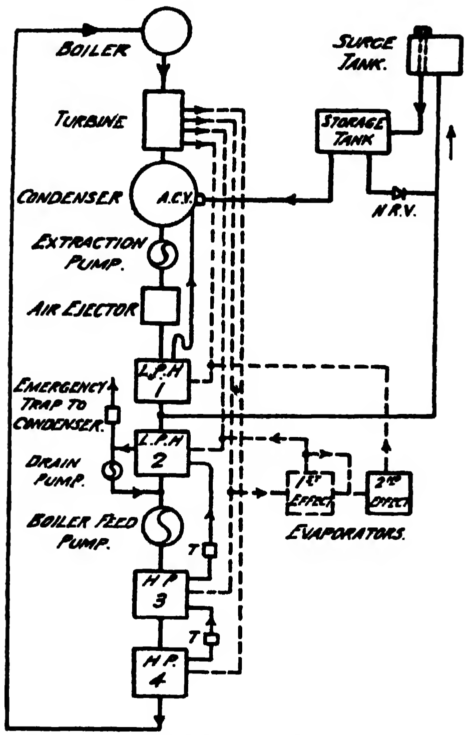


FIG. 351. General Layout of Feed Heating System.

The following indicates the economy obtained in service by an installation of this type :—

Typical Performance of a Feed Heating Turbine Installation

Steam pressure at turbine stop valve		350 lb. g.
Steam temperature at turbine stop valve		700° F.
Vacuum (Bar. 30")		29"
Heat content per lb. of steam at stop valve		1,369 B.Th.U.
Temperature of condensate leaving condenser (t_1) . .		77° F.
Temperature of condensate leaving ejectors (t_2) . .		82° F.
Temperature of condensate leaving No. 1 heater (t_3) . .		136° F.
Temperature of condensate leaving No. 2 heater (t_4) . .		209 F.
Temperature of condensate leaving No. 3 heater (t_5) . .		255° F.
Temperature of condensate leaving No. 4 heater (t_6) . .		300° F.
Total heat input without feed heating	$1{,}369 - (t_2 - 32)$	= 1,319 B.Th.U.
Temperature rise in feed heaters .	$(t_6 - t_2)$	= 218° F.
Added heat to condensate as a percentage of heat input per lb. of steam	$\frac{218}{1{,}319}$	= 16·5 per cent.
Increase in steam consumption due to diverting steam to feed heaters .		= 10·2 per cent.
Heat input with feed heating as a percentage of heat input without feed heating	$\frac{(100-16{\cdot}5)\times(100+10{\cdot}2)}{100}$	= 92 per cent.
∴ Nett saving in heat consumption due to feed heating . .	100 — 92 per cent.	= 8 per cent.

discharge side, also two half-capacity evaporators. The final temperature would be between 260° to 280° F. If a higher final temperature be required, No. 2 heater would have to be moved to the discharge side of the feed pump or alternatively, No. 3 heater would require a large surface and the efficiency of the system would be reduced, due to unequal temperature rises across three heaters.

Four-stage System. The four-stage system shown in Fig. 350 is similar to the previous three-stage system with the addition of a fourth heater and a second-drain pump. Maximum efficiency would be obtained if each heater was fitted with a drain pump, but such a scheme is impracticable. No. 3 heater should be provided with an alternative drain connection through a steam trap to No. 2 heater, and to No. 1 heater with a connection to the condenser, also through a trap. This obviates the necessity of cutting out the feed system in the event of failure of either or both drain pumps. Fig. 351 shows an alternative system and performance figures are included.

General Notes. With the use of high-feed temperatures it would appear that a reduction in total boiler-heating surface could be made, but this is not so. The reasons for this are that, due to bleeding, the turbine steam consumption is increased and the temperature difference between the flue gases and the inlet feed water is reduced. The surface required is inversely proportional to the temperature gradient or difference in temperature between the heating and heated medium, *i.e.*, the smaller the difference the greater is the surface required for a constant rate of heat flow and *vice versâ*. If the feed-water temperature to economiser be raised, the difference between this temperature and the temperature of the flue gases is reduced and the economiser surface must therefore be increased. An alternative would be to include an air heater in the boiler unit if the flue gases are to be cooled to an economical temperature. A high feed-water temperature reduces temperature ranges in the boiler and minimises the stresses set up due to unequal expansion. Further, rapid evaporation is assisted thus promoting better circulation and increasing the effectiveness of the heating surface, and less violent ebullition has the effect of reducing priming. The overall cost of a plant incorporating a feed-heating system is greater than a straight condensing set and the higher the overall efficiency the greater will be the first cost.

The most efficient plant which will pay for itself in the shortest time should be chosen. When feed heating is included the quantity

of steam passing through the exhaust blading to the condenser is reduced. This brings about a considerable saving in first cost in condenser surface, exhaust portion of the turbine cylinder and blading, circulating water pipes and pumps. The saving in circulating water pump power, however small, is continuous throughout the life of the plant. On the other hand, the output of the boiler-feed pump will be increased, due to the larger quantity of steam and further, the cost of steam and feed piping from the boiler to the turbine and feed-heating plant may be higher. All things being equal, a reduction should be possible in the coal and ash handling plants. The quality of the steam is reduced from a superheated to a wet condition during expansion through turbine blading. The particles of water contained in the steam give rise to erosion in the exhaust blading, and a low-pressure bleeding point situated in the wet region of the turbine will help to draw off a portion of this water. The particles of water tend to be thrown outwards by centrifugal force and if the bled-steam connection be made tangential and in the direction of rotation the removal of the water will be facilitated. If live steam at initial temperature and pressure were used for raising the feed temperature, a loss in efficiency would result, equal to the boiler efficiency multiplied by the percentage of steam used plus the decrease in efficiency of the economiser, due to the higher-inlet water temperature. The exhaust steam at the condenser is useless as far as feed heating is concerned, even though the heat content is 900 to 1,000 B.Th.U.'s per lb., since an appreciable temperature gradient must exist before this can be removed. Hence the only feasible method of feed heating is to utilise some of the steam at suitable stages between the turbine inlet and exhaust. The steam bled from the turbine will not have completed its useful work and the additional energy which could have been obtained by expanding it to the exhaust pressure will be deducted from the total gain.

The number of stages of heating to be employed also depends on the capacity of the turbine and the steam conditions obtaining. The operation of this system is automatic, the quantity of steam diverted to each stage being controlled by the temperature and quantity of the condensate passing through the tubes.

The condensate passing through any heater will rise to a temperature within a few degrees of the saturation temperature of the bled steam fed to that heater. However much of the latter condenses it will be replaced automatically from the turbine. Each heater in turn

adds to the temperature of the condensate, and the final temperature is controlled by the temperature of the highest pressure bled steam.

The following arrangements appear to be standard :

30 MW sets (600 p.s.i.) two low pressure and two high pressure heaters with a final feed temperature of 335 $\pm$ 10° F.

60 MW sets (900 p.s.i.) two low pressure de-ærator and two high pressure heaters and final feed temperature at 375 $\pm$ 10° F.

100 MW sets (at present) two low pressure, de-ærator and three high pressure heaters and final feed temperature at 410 $\pm$ 10° F.

Feed-water Heaters. These are of the low-pressure and high-pressure types, the former are on the discharge side of the extraction pump and the latter on the discharge side of the boiler-feed pump. Open or direct contact heaters are also in use and have the advantage that no tubes are required except for the small amount in vent condensers. Absence of tubes obviates some of the operational and maintenance attention usually required with the closed-type heaters. The bled steam mixes directly with the feed water and can heat it to saturation temperature without loss of heat in condensate.

Stations shutting down daily may have live steam high-pressure feed heaters to obtain higher feed-water temperatures on starting up each morning. This minimises choking on the economisers and air heaters due to the deposition of moisture resulting from low feed temperatures during starting up. Local coal characteristics may also aggravate these conditions. The waterboxes and tube nests of the low-pressure heaters are designed to withstand the extraction pump discharge pressure, whilst the high-pressure heaters are subjected to the boiler-feed pump discharge pressure, which is considerably higher than the normal boiler steam pressure. Other low-pressure heaters are : Drain coolers, gland heaters, evaporators and intermediate pressure heaters.

Heaters are of the horizontal or vertical types and site conditions and space available will primarily determine the type to be used. Horizontal heaters can be placed one above the other, sometimes to a height of three or four units. The drain and other low-pressure heaters may be of the horizontal types and the high-pressure heaters of the vertical type. The disadvantage with horizontal heaters is the necessity for a large space for tube withdrawal and in this respect vertical heaters have an advantage, as the tube nests can be easily withdrawn vertically by the station crane. Horizontal heaters are so mounted that drainage is by gravity

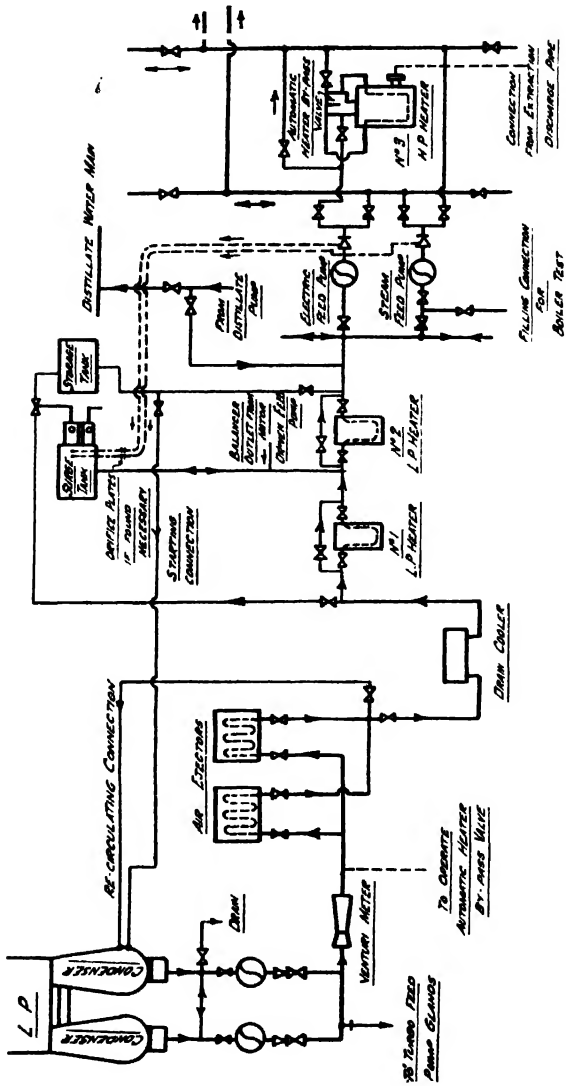


FIG. 354. Condensate System.

avoid strain in the tubes and fixings as the flexible body cannot take much end pressure. The layout and arrangement should be such that all tube nests are accessible and inspection and maintenance on all sections of plant is possible. The heaters are usually situated in the turbine house basement near the turbine end of

the set. The majority of the control valves can have extended spindles for operation from turbine floor level. By careful grouping of the valves it is possible to include a valve control desk which makes quite a feature and facilitates operation. Figs. 352 to 354

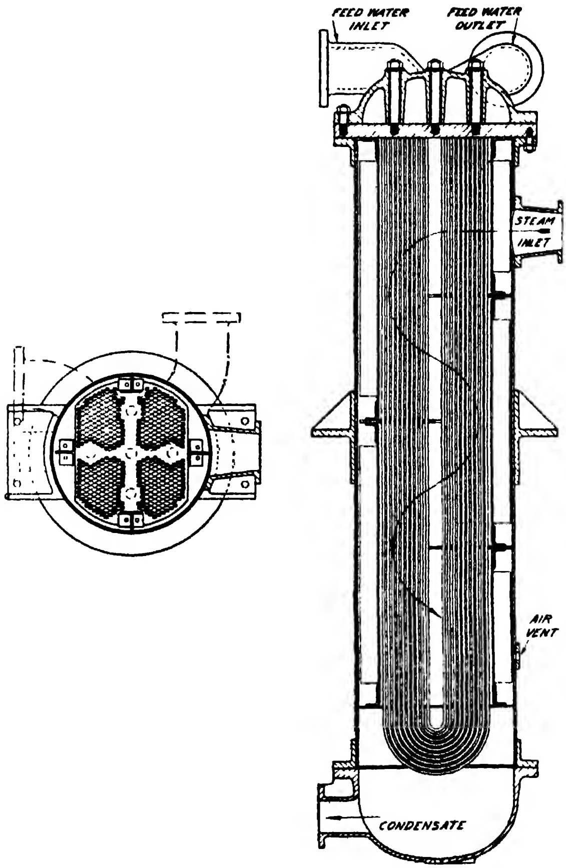


Fig. 355. Longitudinal and Cross Section of Type " U " Feed Heater. (Metropolitan Vickers Electrical Co. Ltd.)

show typical heater connections. Feed-water heaters are steam receivers within the meaning of the Factories Acts, 1937 and 1948, if the steam pressure is one atmosphere (14 p.s.i. absolute) or above.

High-pressure Heaters. The shell may be of boiler quality mild steel or cast steel and the waterboxes and return headers of cast steel. Mild steel baffles are designed to ensure effective distribution

of the steam. A cast-iron or steel condensate well is usual and the tube plates may be of mild steel.

The U-tube type of heater, Fig. 355, has advantages in that the floating header is eliminated which reduces the cost and allows the diameter of the heater shell to be slightly reduced. Baffles are fitted to guide the steam across the tubes and to act as sagging plates. A plate is provided at the bent end to support the tubes when in a horizontal position and to prevent vibration. A faulty tube in the centre of the tube bundle can be removed. The sagging plates being removable leave the plates free to slide down the tubes to the tube plate and the tubes may then be deflected and access provided to the tube to be withdrawn.

The following fittings are included :—

drain and vent cocks for steam and water spaces ; relief valves for steam and water spaces ; thermometer pockets and gauge glass for indicating level of the condensed steam in the well of the heater.

To safeguard the turbine against flooding in the event of a burst tube an emergency automatic by-pass is fitted. A by-pass valve can be arranged to short-circuit two or more high-pressure heaters, a float operated pilot valve being provided on each heater. To prevent starving the boilers when this device operates a by-pass is included through which the feed-water can be supplied to the boilers. The possibility of the water side being isolated with the tubes holding water and steam still supplied must not be overlooked. Very high hydraulic pressures are possible under these conditions and a relief valve should be fitted to the water side. A stop-valve and non-return valve are included in the steam supply.

Gas, steam and electric heating have been used for facilitating the tightening of high-pressure bolting on high-pressure heaters, and turbine casing flanges. A simple and effective method of electric heating is shown in Fig. 356. This permits the bolts to be accurately turned to any pre-determined degree of tightness. The procedure is first to place the bolt in position and screw it hand tight by means of a spanner. A carbon electrode is then inserted into a hole in the bolt and the current switched on, rapidly heating the bolt. The nut is then rotated by hand through a predetermined radius and when the tightening is complete the current is switched off. This method is also used in unscrewing the bolt thus obviating stripped threads by reducing the pressure before the nut is turned. The same method is applicable to studs as well as bolts. To tighten

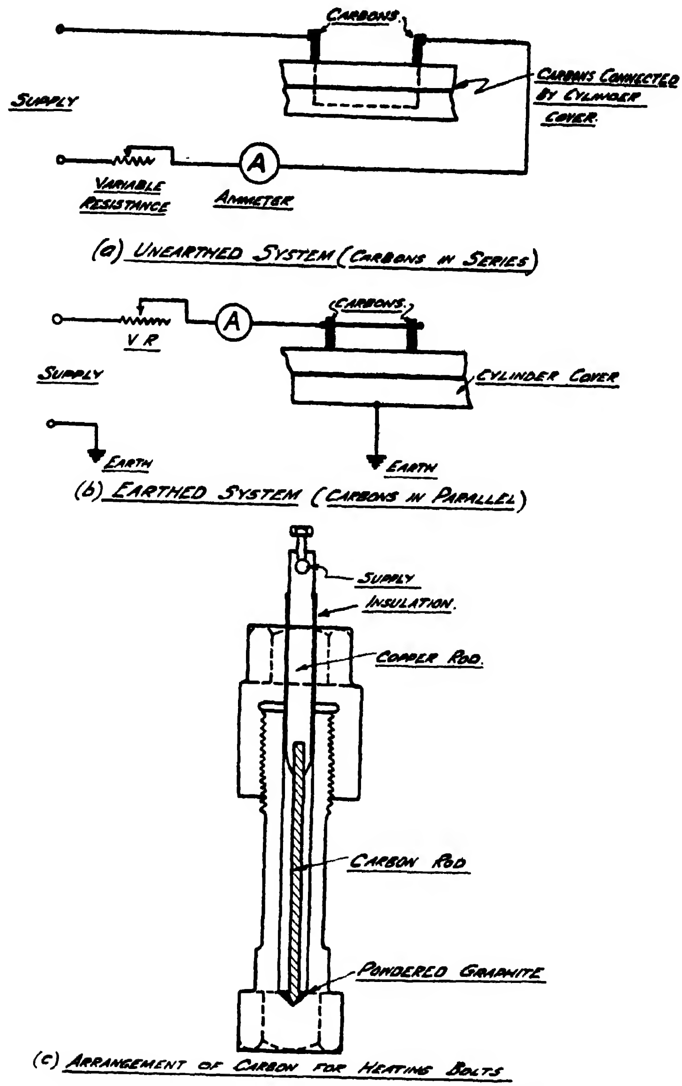


FIG. 356. Method of tightening High-pressure Bolts.

large bolts about fifteen minutes are required for one-third turn. A single phase transformer 380/80 volts, with 80/90 amps. flowing in the secondary heated two bolts connected in series in about fifteen to twenty minutes on a turbine casing joint.

On joints where fitted bolts are provided these should be removed first before slacking off any of the other bolts in a joint. The fitted bolts should be a light fit only and if the other bolts with clearance holes are slacked off first slight movement may follow resulting in the fitting bolts being jammed.

Low-pressure Heaters. Waterboxes, floating headers, doors and bodies are of cast iron or fabricated mild steel. High pressures and temperatures are not experienced as the bled steam has usually been reduced to a wet condition in the turbine.

The fittings include :—

drain and vent cocks for steam and water spaces, relief valve for water space, water gauge glass and thermometer pockets, inlet, outlet and by-pass feed water valves for each main heater. Non-return and stop valves in steam supply piping.

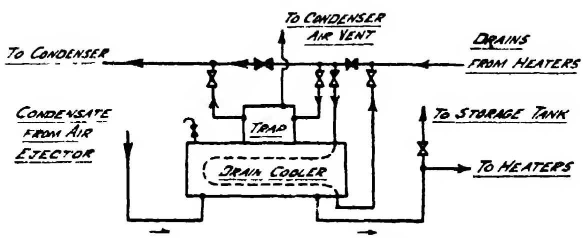


Fig. 357. Drain Cooler.

Drain Coolers are similar to the low-pressure heaters except that the tubes may be expanded at one end and ferruled at the other to allow for difference in expansion between the tubes and the shell. A floating header type of heater used as a drain cooler would allow the water to flow through the space surrounding the tube nest thus short-circuiting the tubes and impairing the efficiency of the cooler. The space results from the area occupied by the flanges and bolting of the floating head, but is not a disadvantage in a steam heater as it allows the steam free access to all parts of the tube nest. Fig. 357 shows typical connections.

Gland Heaters are included for utilising the heat in the steam leaking from the high-pressure turbine gland. By-pass feed water valves for auxiliary heaters and the usual fittings are supplied.

Tubes for condenser service are dealt with in Chapter X. To limit the number of tube-fixing tools the diameters and thicknesses of tubes should be as few as possible. Smaller tubes permit of a smaller tube plate and waterbox. The unsupported length of a tube should not exceed about ninety times the diameter of the tube.

In the determination of tube thicknesses for heaters, corrosion and the minimum thickness for expanding are often the limiting factors. When experience fixes a tube thickness to withstand corrosion for a reasonable period of years, the stress is generally within working limits. Tube diameters vary between $\frac{5}{8}$ to $1\frac{1}{4}$ in.

Tube ends which are to be expanded into the tube plate should be annealed, but ends which are to be fixed by means of packed glands and ferrules should be left in a hard condition to withstand the pressure of the packing without reducing in diameter.

Tube materials should possess ductility to facilitate drawing operations and resistance to corrosion is also desirable, particularly in a system where air may be present or on a machine which is to be shut down and restarted at frequent intervals. A plant in operation is not so liable to corrosion as during shut-down periods, when air can gain access to heaters which contain moisture from the condensed steam.

Materials used are copper, admiralty mixture, brass and mild steel and in special cases stainless steel and cupro-nickel alloys. Solid drawn mild steel tubes are favoured for their low cost. Steel tubes may be used in their normal condition exactly as drawn or they may be specially treated to withstand corrosion. In practice it has been found that tube leakage may occur due to the general effect of "copper shortening." Where temperature changes obtain over a period of service a copper tube may be reduced in diameter and result in leakage past the expansion in the tube plate. Cupro-nickel tubes are used in all heaters working at the higher temperatures. 300° F. and above. Galvanising by electro-depositing or dipping, or protection by metal spraying is not permissible for tubes which have to be expanded and possibly bell-mouthed, as the protective layer of metal would be broken by the expanding tools. The property of being able to flow with the tube material during expanding is an advantage. The process known as sheradising meets these requirements and is cheaper than tubes drawn from special alloys. The process is carried out by packing into steel containers the articles to be treated together with the requisite quantity of zinc dust. The latter is produced by the distillation of pure zinc and is more chemically active than solid zinc. The container is then sealed and heated in a furnace which brings about an amalgamation of the two metals. The iron becomes impregnated with zinc and a zinc iron alloy is formed with the surface material of the base metal. This rust-proof protective coating will not peel off, but will flow with the metal if bent. This

property makes the process suitable for heater tubes as the protective coating is not destroyed by expanding or bell mouthing of the tube ends. Further, normal sherardising only produces a surface dimensional increase of about 0·001 in. A heater containing steel tubes should have about 15 per cent. more surface than one having copper tubes.

Data relating to three installations are given :—

30 MW—650 lb. per square inch—850° F.—340° F. Final Feed Temperature.

Drain cooler . . .	700 sq. ft.	
No. 1 low-pressure heater.	600 ,,	
No. 2 ,, ,, ,,	900 ,,	
Intermediate heater .	620 ,	After boiler feed pump.
High-pressure heater .	500 ,,	After boiler feed pump.

50 MW—600 lb. per square inch—825° F.—265° F. Final Feed Temperature.

Low-pressure heater	. 1,400 sq. ft.	—680 tubes, $\frac{3}{4}$ in. dia. brass.	
Intermediate heater.	. 1,400 ,,	— ,, ,, ,, ,,	
High-pressure heater	. 1,370 ,,	—1,048, $\frac{5}{8}$ in. dia. copper.	
Thickness of brass tubes	= 0·048 in.	(10 ft. 6 in. long).	
,, ,, copper tubes	= 0·080 in.	(8 ft. 0 in. ,,).	

All tubes roller expanded.

A gland heater and drain cooler are also included.

30MW—300 lb. per square inch—750° F.—290° F. Final Feed Temperature.

Drain cooler . . .	350 sq. ft.—2 flows. 298 tubes, $\frac{3}{4}$ in. outside diameter, 70/30 mixture brass expanded both ends, 14 S.W.G. Waterboxes and tube nest tested to 100 p.s.i. hydraulic pressure. Body tested to 50 lb. p.s.i. after tubing.
Low-pressure heater .	1,070 sq. ft., 6 flows. 840 tubes, $\frac{3}{4}$ in. outside diameter, 70/30 mixture brass expanded into tube plates at both ends, 14 S.W.G. Bellows-type body takes expansion. Tests as for drain cooler.
High-pressure heater No. 1	675 sq. ft., 6 flows, " U " type. 170 tubes, $1\frac{1}{8}$ in. outside diameter, copper, 12 S.W.G., expanded into waterbox. Waterbox, tube nest and end door tested to 1,100 p.s.i. hydraulic pressure. Body tested 50 lb. p.s.i.
High-pressure heater No. 2	620 sq. ft., 6 flows, " U " type. 170 tubes $1\frac{1}{8}$ in. outside diameter, copper, 12 S.W.G., expanded into waterbox. Waterbox, etc., as for No. 1. Body tested to 125 p.s.i. hydraulic pressure.

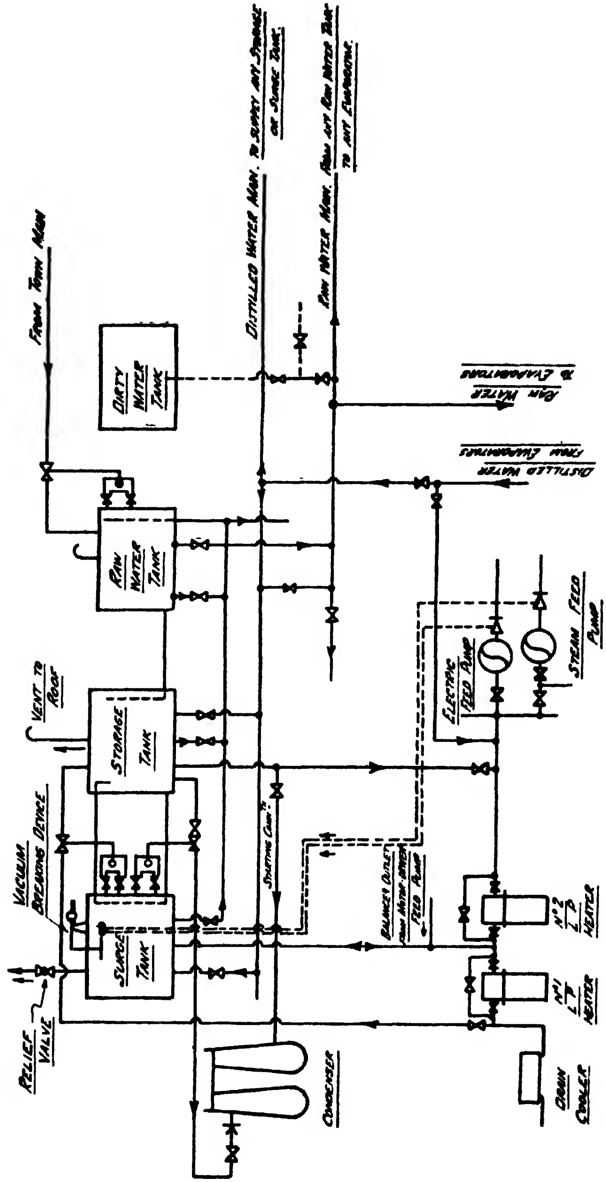


FIG. 358. Arrangement of Water Make-up Tanks.

Gland Steam Condensers condense excess steam, the gland drains always being open to the condensers. The condensers are themselves drained to waste *viâ* an open tundish which enables the operator to determine the correctness of the steam supply to the glands. The drains from the gland steam distribution boxes are taken to the drain tank. The cooling water is taken from the extraction pump discharge line.

Glands of the low-pressure cylinders may require sealing water and this may be taken from the surge or storage tank if a special gland tank is not included.

Tanks associated with a feed system are surge, storage and drain tanks. In some stations there are one or more large reserve or storage tanks with smaller surge tanks controlling fluctuations on each set. One arrangement is shown in Fig. 358.

The surge tank maintains a constant static head on the boiler feed pump suction, as the head at this point should be above the pressure corresponding to the pressure of the water, otherwise vaporisation may occur causing cavitation and erratic operation of the pump. The tank further serves to maintain an almost constant head on the extraction pump. If the tank is for purely surge purposes its capacity could be about 5 per cent. of the total water volume of the boilers with which it works. Should storage be taken into consideration a tank of reasonable capacity is desirable since the allowable tank outage time will be increased. Assuming a 30 MW set to take 300,000 lb. of steam per hour, and a make-up of 3 per cent. be allowed for, then 9,000 lb. of water per hour for make-up would be necessary. Tanks of 10,000 to 20,000 gallons capacity are common and inter-connecting arrangements are made with tanks from other sets. Surge tanks are sometimes steam-sealed by the exhaust from de-aerators or other auxiliaries. Boiler feed pump leak-offs at light loads discharging into surge tanks may result in air being taken into the condensate system when connections are above water level.

Storage tanks are required for both feed water and raw water, the latter being used for general services. Raw water may either be taken from a river, canal or sewage effluent with an emergency connection from a town main. Local conditions will determine the arrangements to be made for this water.

A tank (Fig. 359) is usually provided for collecting all clean water drains, discharges from steam traps, leakage from feed pump glands, leak-off from feed pump non-return valves, etc. When a turbine is being shut down the necessary drain valves are left open

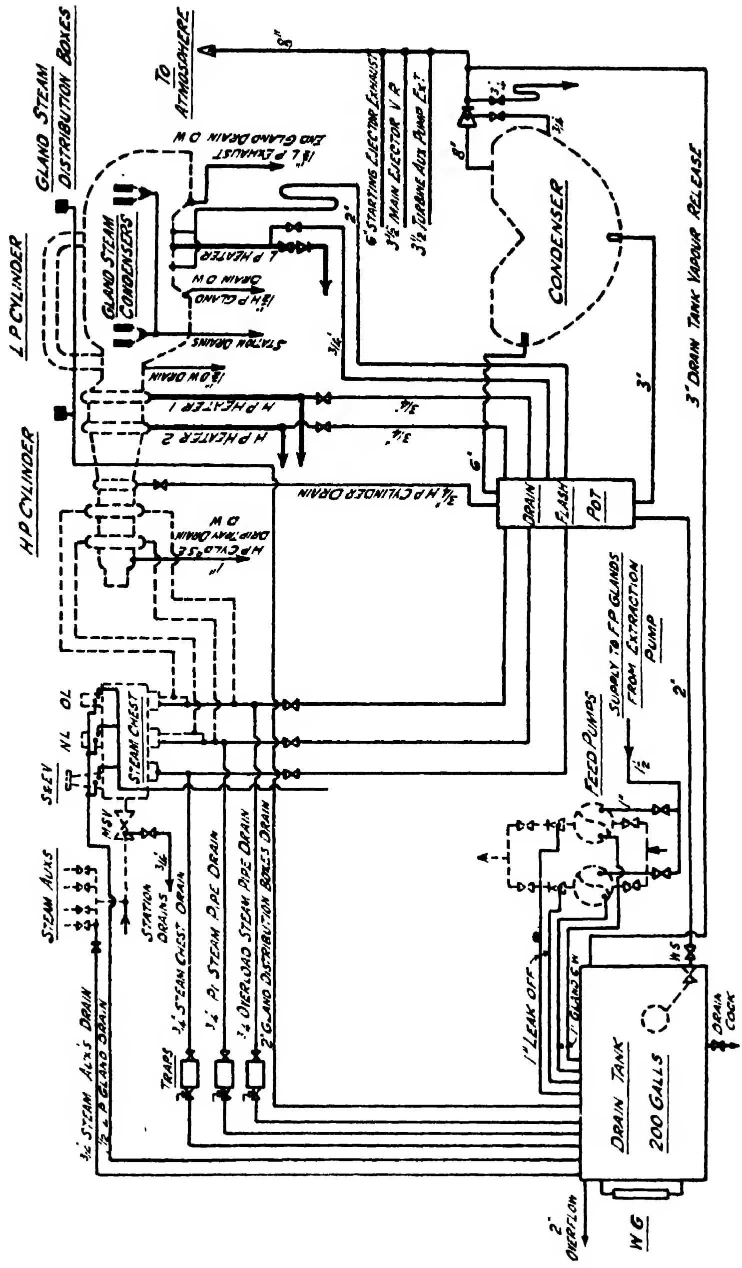


FIG. 359. Diagrammatic Layout of Turbine Drains.

to rid the different sections of water formed during cooling down. On starting up, the lower part of the stop and emergency valve will be subject to vacuum and the water formed when steam is first turned on to the cold parts will require draining to a point of equal or lower pressure and will thus necessitate it being drained to the condenser by way of the hot well, flash box or condensate receiver. A trap is included to prevent continuous blow through of steam which would otherwise take place as there cannot be any form of visual observation. When a turbine is on load but not in excess of economical rating the overload steam valve is shut and there is no flow of steam through the loop or "U" pipe. A small amount of steam may be condensed and it is usual to lead this drain *viâ* a trap to the drain tank or alternatively to the vacuum space. Steam pipe loop and other drains which are under vacuum during starting-up periods should all be taken to a flash box *viâ* the by-pass and normally through a trap as indicated. The tank is arranged to discharge to the condenser automatically for de-aeration. An unrestricted flow of steam and/or water to the condenser hot well may interfere with the working of the closed feed control valve which governs the water level in the condenser. An orifice plate in the trap by-pass and a regulating valve in the trap circuit are useful. The tank water may be discharged to the surge or storage tanks by a motor operated pump controlled by float valve mechanism.

The surge, storage and raw water tanks may be placed on a separate floor, immediately above the feed pump bay. Storage and raw water tanks are sometimes placed on the boiler or turbine house roofs. Surge and storage tanks may be of mild steel, cast iron or "Armco" iron. Welded or riveted forms of construction are suitable and the tanks should be adequately strutted and braced. Manholes are included on the covers of each tank and interior ladders give access to the tank. Where float gears are necessary these should be housed in separate chambers, provision being made for isolation from the tanks to facilitate inspection and maintenance whilst the tanks are in service. Water level gauges and distance level indicators are included and vent pipes or vacuum relief valves may be necessary. The latter are essential on the surge tank if the feed pump leak-off is taken to this tank as the water may be heated. Cases are on record where a vacuum was created which resulted in completed collapse of the tanks.

Raw water tanks may be constructed in a similar manner to the

surge and storage tanks, but if sewage effluent is used for services, then " Armco " iron or cast iron is desirable. The advantage of the former is that riveting or welded construction is possible. Mild steel is suitable for drain tanks. Tanks for one large set are :—

Surge tank .	20,000 gallons	—½ in. thick	—" Armco " iron.				
Storage tank .	,,	,,	,,	,,	,,	,,	
Raw tank .	,,	,,	,,	,,	,,	,,	
Drain tank .	10 gallons	—⅛ in. thick	—galvanised mild steel.				

Boiler Feed Pumps. These are without doubt the most important auxiliaries in the feed heating system, and reliability is the essential feature. The modern boiler has a very large evaporative capacity but very little water space, and further, the water in circulation is only a very small proportion of the amount evaporated per hour. A centrifugal pump is chiefly used as the main pump, but booster pumps may be of the direct acting type. The centrifugal pump can be designed to give any desired pressure when discharging a given volume of water. The discharge pressure of the pump varies as the volume of water discharged is varied, and the character of this variation, which is termed the pressure-capacity or H-Q characteristic, is important. The upper curve, ABCD (Fig. 360) shows the type of characteristic obtained with centrifugal pumps when consideration is not given to their design. Such a characteristic is not only unsuitable for boiler feed pumps, but leads to difficulties in operation and may even be dangerous by causing surging. It will be observed that the pump can operate at two widely different capacities such as B and C at the same discharge pressure. The discharge pressure is determined by the boiler pressure plus the static, and frictional resistances between the feed pump and the boiler inlet. When the quantity required by the boilers is between two such capacities, surging may be experienced. The pressure-capacity characteristic may be made so that the pump is inherently stable. To enable pumps to operate satisfactorily in parallel the discharge pressure developed by the pump should be a maximum when no water is flowing and fall continuously as the quantity of water through the pump is increased. The characteristic of such a pump is shown by the lower curve EF. If two pumps having a pressure-capacity characteristic such as shown by curve ABCD (single pump) are operated in parallel, the combined characteristic of the two pumps would be as shown by the curve AHJ. (two pumps), if the two pumps share the load equally throughout the total range of capacity. It will be noticed that one pump may be

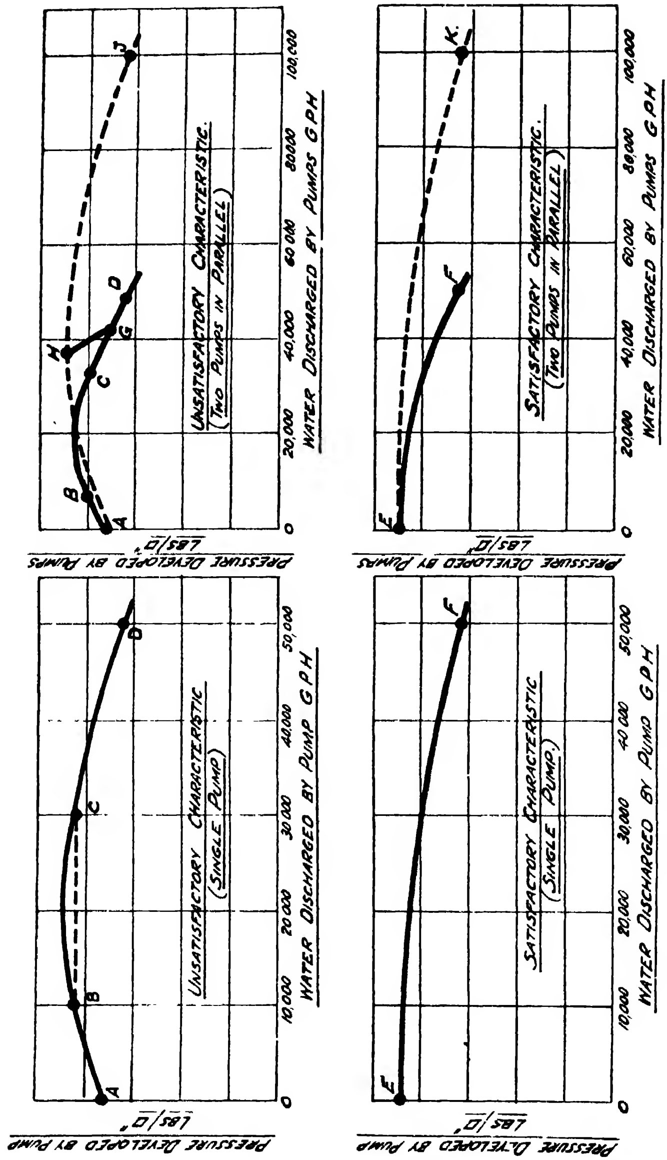


Fig. 360. Feed Pump Pressure-capacity Characteristics.

delivering all the water up to a quantity AG, while the other pump is idling, in which case the characteristic for the two pumps is as shown by ABCGHJ.

It is dangerous to operate a pump for any length of time without a reasonable flow of water through it, because the work done in overcoming friction by churning the water is converted into heat. This may cause the water in the pump to boil and result in excessive temperatures causing seizure of certain parts. These difficulties are eliminated with pumps having a characteristic as shown by EF. A leak-off arrangement is included in the main non-return valve so that there is a continuous flow of water. Trouble has been experienced with the leak-offs due to excessive leakage, but this may be overcome by including a nozzle plate in the pipe line. Curve EK shows the combined characteristic of two such pumps working in parallel and it will be seen that for any given pressure in the feed range there is only one corresponding quantity of water. The tendency experienced with all pumps to increase the quantity of water discharged will always be accompanied by a fall in the discharge pressure, so that any possibility of a pressure wave being started is immediately counteracted and surging is prevented. Further, pumps having the same characteristic share the load equally at all times, and in so doing operate at maximum economy. Pumps having different capacities but having similar pressure-capacity characteristics will share the load in proportion to their respective maximum capacities.

For boiler feeding purposes it is desirable to reduce the fall in pressure between no-load and full-load to a minimum. A fall in pressure of about 10 per cent. of the pressure at full load is usual. Although the pressure rise may be low, excessive pressure in the feed range at light loads is occasionally experienced. This excessive pressure may cause blowing of the economiser relief valves with consequent loss of feed water and unsatisfactory operation of the boiler check-valves due to high differential pressure.

Referring to Figs. 361 and 362 it will be appreciated that the pump is only partly responsible for this state of affairs. Economiser friction increases the pressure required to EG, and the friction in feed heaters, piping, valves, etc., gives a total required pump pressure represented by curve EH. The pump must therefore be designed to give pressure H at full output and KH represents the pressure developed by the pump at varying loads and constant speed. The excessive pressure is shown shaded, and it should be noted that portion above line LH is attributable to the pump, the remainder being due to friction losses in the feed system. Curve KF gives the pressure at the inlet side of the boiler check-valves, and it

will be apparent that the difference between KF and AB may be appreciable at light loads. Excessive pressure may be eliminated by speed regulation and a saving in power effected on light loads. Combinations of steam and electric feed pumps are adopted.

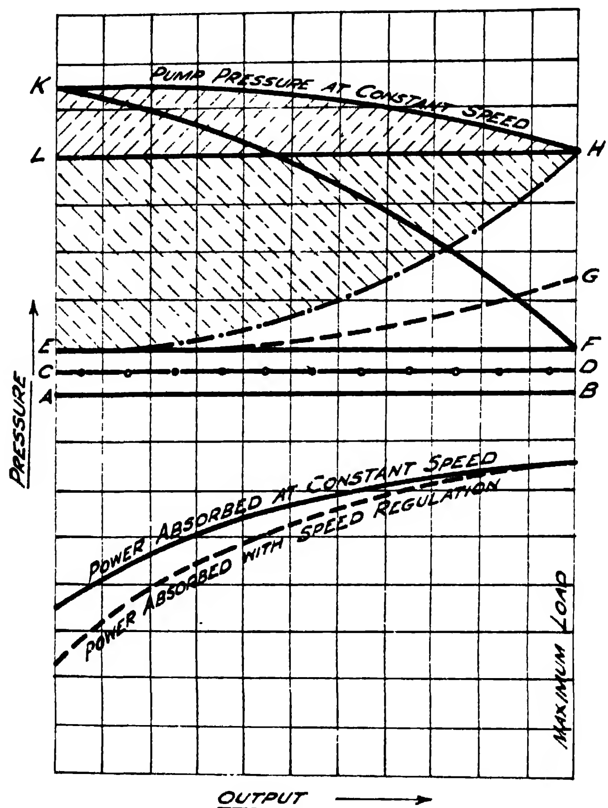


Fig. 361. Boiler Feed Pump Characteristics.

AB—Normal working boiler pressure.
CD—Boiler blow-off pressure.
EF—Pressure required at boiler check valves.
EG—Pressure required at economiser inlet.
EH—Pressure required at pump.

The problem of unnecessary excessive pressure across the feed regulators has also received careful consideration. Messrs. Weir & Co. have developed a turbine-driven booster pump which operates in series with a constant speed, high efficiency electrically-driven pump which generates a pressure approximately equal to the boiler

pressure. The steam supply to the booster pump is controlled from the pressure on the boiler feed range, and its speed is varied so that the booster pump creates in the suction of the electrically-driven pump such added pressure as is necessary to maintain the correct feed pressure in the feed range at all loads. Some engineers consider

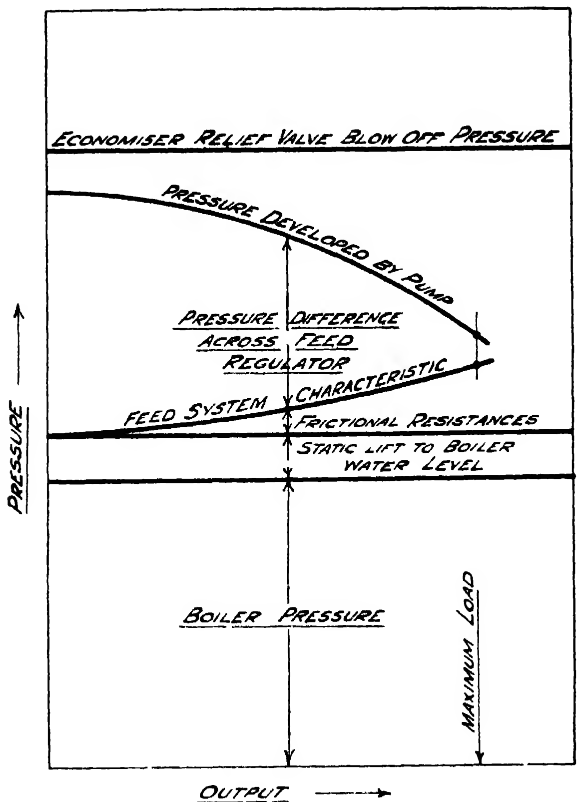


FIG. 362. Pressure-capacity Characteristics of a Boiler Feed Pump and Feed System.

that on estimating the pump pressure, allowance should be made for the pressure at which the boiler safety valves are set, whilst others are of the opinion that normal drum pressure should only be catered for. This has the effect of reducing the power required for the driving motor by an appreciable amount. A condition demanding the maintenance of maximum pressure exists when the safety valves are blowing due to a sudden and unexpected reduction in

load. On giving this consideration, it appears reasonable to assume that when the drum valves are ready for blowing off, the volume of feed water can be reduced. This means that the pumps could work to some extent up to their pressure-capacity characteristic and it is feasible to base the calculations on normal drum pressure. In order to deal with the conditions arising at no-load the economiser relief valves should be set at a pressure to cover the excessive pressure generated due to the characteristic of the pumps. When the boiler load is suddenly increased it may be necessary to reduce temporarily the feed, owing to a rise in water level in the drum due to bubble formation. Excessive feed-water pressure at the boiler check valves over the steam pressure may result in flooding the boiler owing to the check valves being unable to close sufficiently against an excessive pressure difference.

Trouble has been experienced with high pressure (1,100 p.s.i.) pump casings due to porosity of the metal. Another problem demanding attention is the choice of plain or roller bearings for both pump and motor. Although the former are more expensive it is generally found that they give better service.

In some recent high-pressure stations the main boiler feed pumps are of the vertical reciprocating type. This type of pump was chosen in preference to a centrifugal pump on account of its higher efficiency and comparatively flat characteristic curve. Another advantage is that the speed is very low compared with that of a centrifugal pump. The design efficiency of the reciprocating pump was 86 per cent., whereas a figure of 60 per cent. was expected for a centrifugal pump. Further, the reciprocating pump maintained approximately the same efficiency down to about 25 per cent. load, whilst the efficiency of the centrifugal pump at the same load was only 24 per cent. A slow speed reciprocating pump is more expensive than a centrifugal pump, and it is usual to make the stand-by or emergency pump of the latter type, and drive by steam turbine. Reciprocating pumps occupy more space and the capital cost is higher and, furthermore, smoother delivery pressures are obtained with the centrifugal type.

The particulars of the reciprocating pumps referred to are :—

5 Throw—12 in. stroke—$5\frac{1}{2}$ in. dia. ram ; 240,000 lb. of water per hour ; 100 r.p.m. ; 800 H.P. direct current variable speed motors, driving pumps through gears ; cylinders are water-cooled. On test the efficiency of the pumps and gears was 89 per cent. at full load.

If the pumps are in the boiler house they should be in a separate

room to eliminate coal dust and dirt entering bearings and glands.

The pumps should be situated between the boilers and turbines,

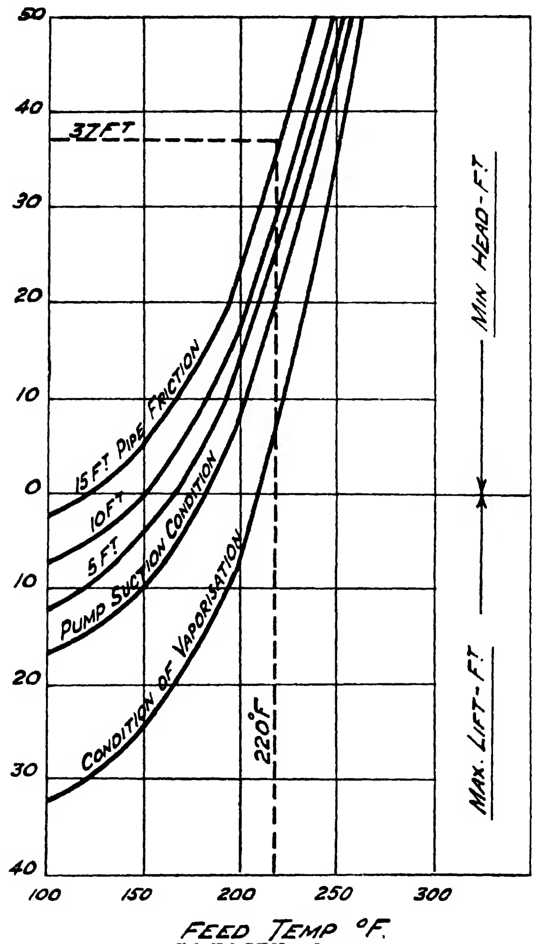


FIG. 363. Boiler Feed Pump Suction Conditions.

and this is achieved by forming an annexe as shown in building drawings, Volume 1, Chapter II. If possible the pumps should be at firing-floor level, which is usually at turbine operating floor level.

The layout of pumps and piping depends largely on site condi-

tions obtaining, but simplicity and accessibility should always be borne in mind. The position of the feed pump in the system depends upon a number of factors. The various systems outlined have shown the necessity for some form of storage tank which at certain conditions of operation affects the pressure on the suction side of the feed pump. The lowest curve in Fig. 363 shows the pressure

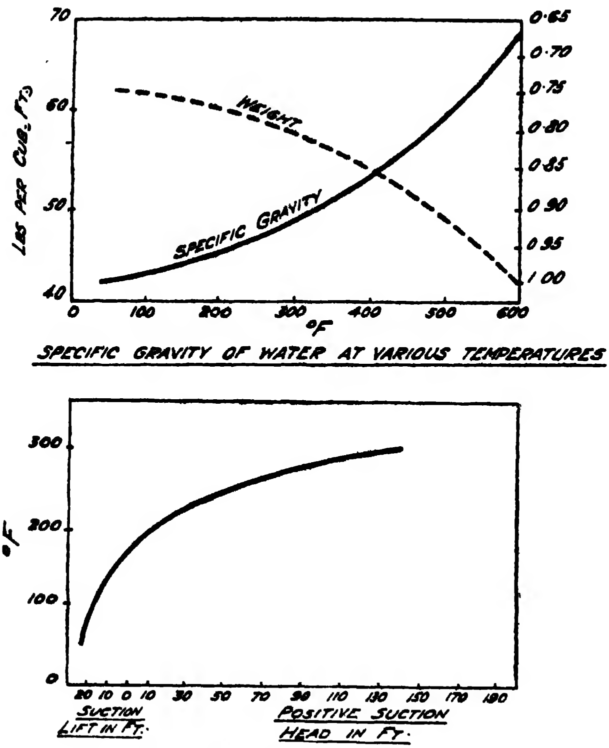


FIG. 364. Feed Water Characteristics.

expressed in feet head of water column at which water at various temperatures will boil, for example, water at 220° F. will boil at a pressure above atmosphere equal to that exerted at the base of a column of water 6 ft. high. If water at this temperature is taken to a feed pump its pressure must be such that ebullition does not occur, otherwise the pump would have to deliver a mixture of water and vapour and its output would be reduced due to the volume of vapour so formed being much in excess of the volume of water.

Water gives off a considerable quantity of vapour even before the boiling temperature is reached. To ensure the pump does not become vapour-locked, the water must be supplied at such a pressure that no vapour will be formed and the second curve shows the minimum pressure required at the feed pumps for various temperatures of water being pumped ; the difference between the two lines represents a margin of 15 ft. The water in an open surge tank must also be kept at a temperature which will prevent vapour

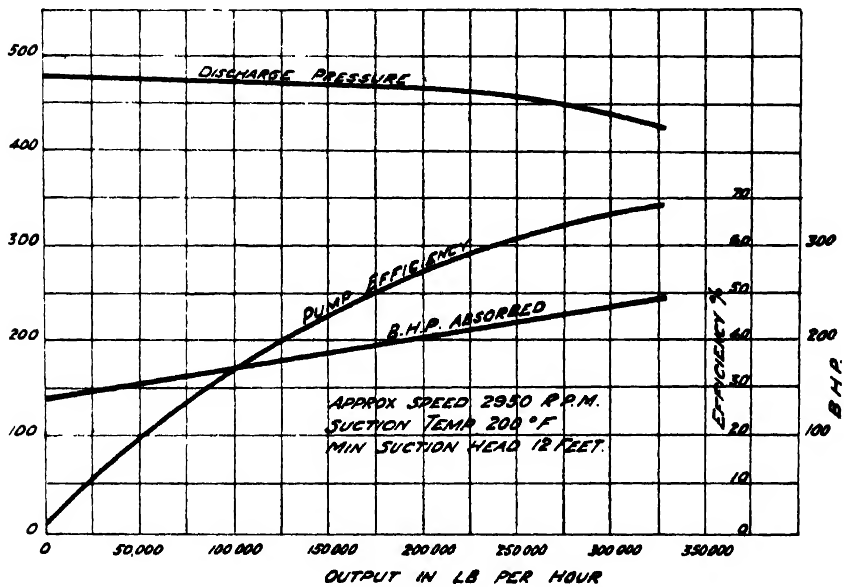


FIG. 365. Typical Boiler Feed Pump Characteristic Curves.

forming to the atmosphere, thus the tank is connected to a point where the temperature is about 100° F. to 170° F. This connection is below the low-pressure heaters, and when water is flowing along the feed main there will be a lower pressure at the feed pump suction than at the point of connection of the surge tank due to the resistance to the flow. The relative position of the above points will affect the magnitude of flow resistance, and the next three curves show the effect of the friction between the two points is 5, 10 and 15 ft. Thus if the friction head is 15 ft., the minimum level of the bottom of the tank will need to be 37 ft. above the centre line of the feed pump suction.

In general a temperature of 220° F. is the maximum permissible at the boiler feed pump suction when the pump is mounted on the turbine floor level, but can be slightly exceeded if the pump is at basement floor level. The curves rise steeply and it will be observed that if the water at the feed pump suction be increased to 250° F. the surge tank would have to be located on a floor about 70 ft. above the pumps.

To illustrate the procedure adopted in estimating the pump heads and capacities the following example is given :—

A 30-MW turbine is served by three boilers, each having a maximum continuous rating of 187,000 lb. of steam per hour and a normal economical rating of 150,000 lb. per hour. The pressure and temperature at boiler outlet is 600 lb. per square inch gauge and 850° F. Temperatures of water at boiler feed pump suction are 220° F. and 160° F. at maximum and no load respectively.

Assuming 10 lb. of steam per kW. hour, then total steam required = 30,000 × 10 = 300,000 lb. per hour. One motor-driven pump and one steam turbine pump would probably be installed. The boiler and turbine contractors supply certain data and actual pressure conditions are required at the feed range outlet based on the maximum continuous rating of the boilers.

The data supplied by the boiler contractor are :—

	Based on Drum Pressure (lb per sq. inch)	Based on Safety Valve Load
Pressure at superheater outlet	600	—
Pressure drop through superheater	40	—
Drum pressure at M.C.R.	640	—
Safety valve on drum	—	685
Boiler check valves	5	5
Auto feed regulator	25	25
Economiser inlet valve	5	5
Drop through economiser	18	18
Friction losses in pipes	10	10
Total inlet pressure at feed range outlet	703	748

The data supplied by the turbine contractor are :—

	lb per square inch.
Loss through high-pressure heaters and valves	12
Suction pressure at feed pump inlet due to extraction pump (or storage tank)	7
The static head between feed range outlet and feed pumps	14
Loss through delivery piping and range	10

The particulars obtained can now be tabulated as follows :—

	lb per square inch.
Maximum Load Conditions :	
Boiler inlet pressure at feed range outlet	703
Static head down to feed pumps	14
Loss through heaters and valves	12
Loss through delivery piping and range	10
Head at feed pump discharge	739
Less suction pressure at feed pump inlet	7
Net head generated by pump	732
No Load Conditions :	
Head at feed pump discharge	739
Increase in pressure at no-load due to pump characteristic .	96
Allowance for increase in pressure due to increase in density of water from 220° F. to 160° F. (approx.) . . .	18
	853
Less static head	14
Maximum pressure at feed range outlet	839

The economiser safety valves would be set at 875 p.s.i.

The positive head on the pumps will therefore be 739 p.s.i. and the net generated head 732 p.s.i. based on water at 220° F., and these figures must be obtained at full load when dealing with 300,000 lb. of condensate per hour, any margin required for design being added thereto.

The specified temperature is very important, for as this varies so must the linear dimensions of the pump be varied in order that the requisite weight of water shall be fed into the boilers in a given time. A centrifugal pump will deliver a given number of gallons of water to a specified head in feet, and further, the volume and head remain constant with varying temperatures, but due to the specific gravity changing with the temperature it should be noted that the amount of feed measured by weight, and also the pressure developed, drops as the temperature is increased.

A pump for 300,000 lb. of feed per hour against a working pressure at the pump outlet of 750 lb. p.s.i. designed to deal with cold water (10 lb. per gallon) would be arranged to pump 30,000 gallons of water per hour against a pressure of $750 \times 2{\cdot}3 = 1{,}730$ ft. Assume that temperature of this water be raised to 250° F. It will be observed from Fig. 364 that the specific gravity at this temperature is 0·945, under which condition a gallon of water weighs 9·45 lb. The boilers require 300,000 lb. of feed per hour,

which divided by 9·45 = 31,800 gallons per hour. The fact that the temperature of the water has been raised to 250° F. will not alter the volumetric capacity of the pump. Thus with the pump designed for 30,000 gallons per hour the output is low in the

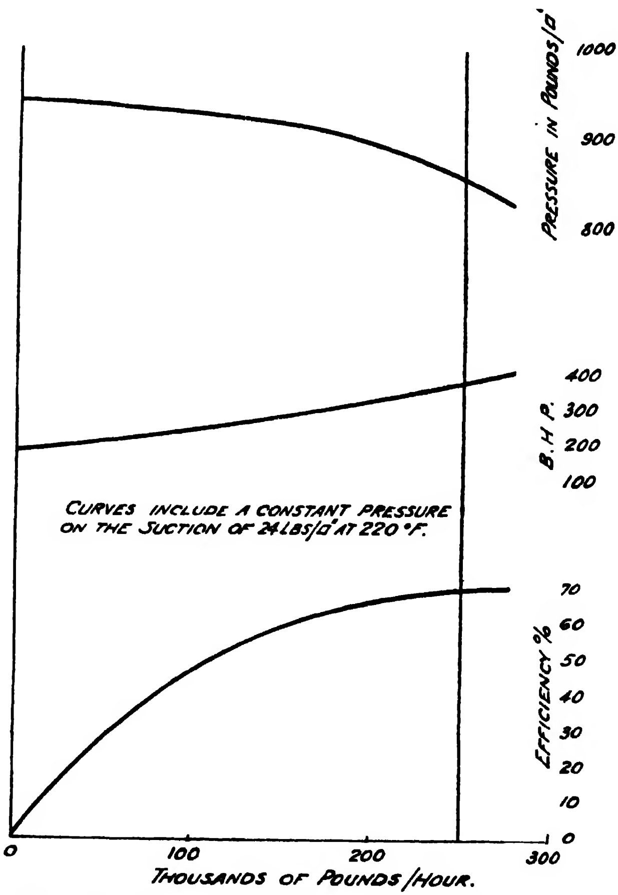


FIG. 366. Electrically Driven Boiler Feed Pump 5″/6″—3,000 R.P.M.

ratio of 30,000 to 31,800, viz., 5 per cent. To maintain a pressure of 750 p.s.i. at the pump outlet with water having a specific gravity less than unity, demands a column of water greater than 1,730 ft., the actual height of the column in the case being $\frac{1,730}{0 \cdot 945}$ = 1,830 ft. Thus in addition to the pump having larger internal

passages it must also have impellers of a greater diameter in order to develop the extra head. The B.H.P. required to drive the pump is also dependent upon the specific gravity, *i.e.*,

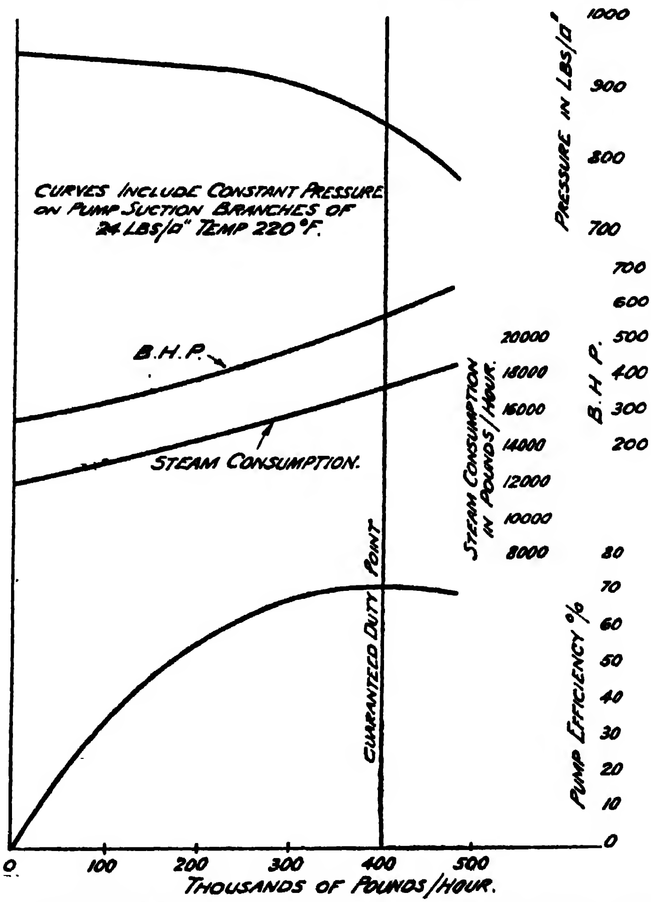


FIG. 367. Electrically and Turbine Driven Boiler Feed Pumps 6″/7″—3,000 R.P.M.

$$\text{B.H.P.} = \frac{\text{gallons per hour} \times \text{feet head} \times 10 \text{ lb. per gallon}}{33{,}000 \times 60 \times \text{pump efficiency}},$$

or under hot-water conditions in example,

$$\text{B.H.P.} = \frac{31{,}800 \times 1{,}830 \times 9{\cdot}45}{33{,}000 \times 60 \times \text{pump efficiency}}.$$

When dealing with hot water, consideration should be given to

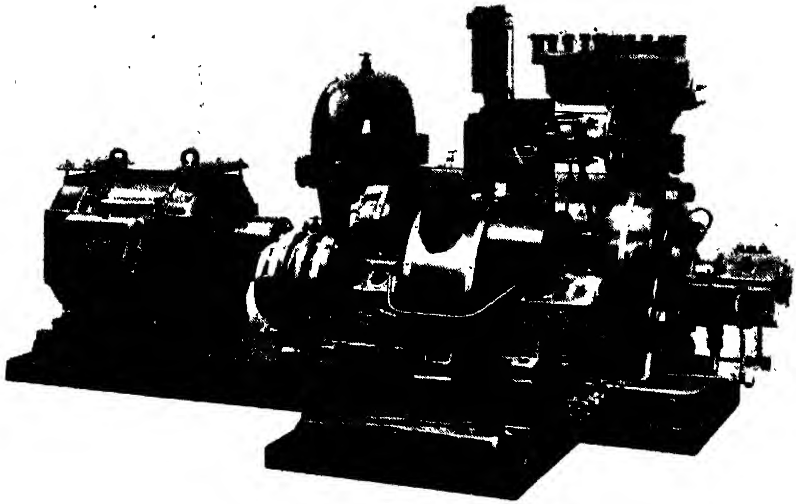


FIG. 368. Turbo-electric Feed Pump, 250,000 lb. per hour, Discharge Pressure 550 p.s.i. (G. & J. Weir Ltd.)

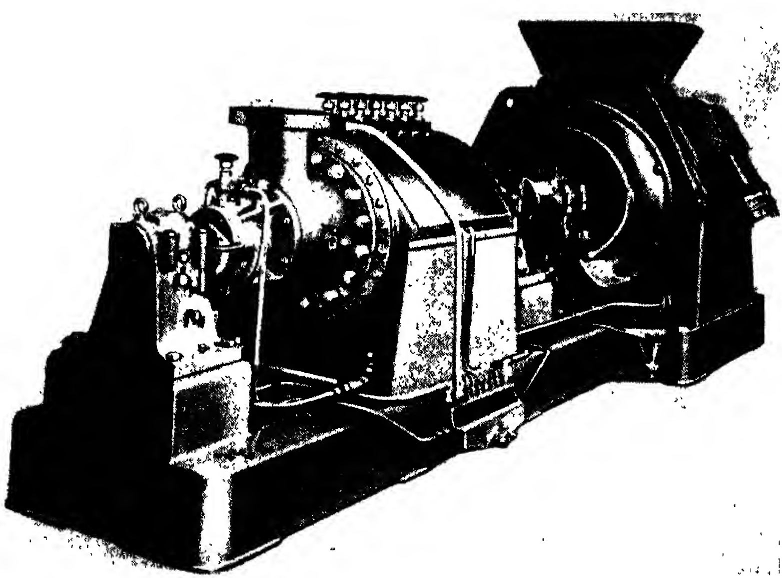


FIG. 369. Motor-driven Boiler Feed Pump. (Harland Eng. Co. Ltd.)

the head under which the water flows into the pump and the design of the inlet pipes. The vapour pressure of the water, *i.e.*, the critical point at which it no longer remains liquid, but turns into vapour depends on its temperature. Fig. 364 shows the pressure at which the water should be held at the pump suction as a function of the temperature. This curve maintains a suitable margin over and above the critical pressure. It should be observed that at a tempera-

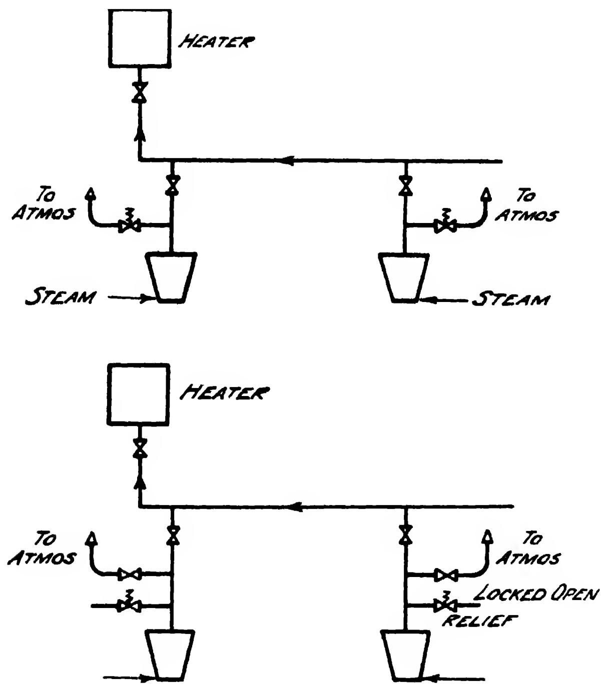


FIG. 370. Steam Feed Pump Exhaust Arrangements.

ture of 170° F. the water should be led rather than drawn into the pump suction. At or beyond this figure a pressure head increasing with the temperature is necessary. Figs. 365 to 367 show typical feed pump characteristic curves. Figs. 368 and 369 illustrate two modern pumps, whilst Fig. 370 shows the exhaust arrangements for steam pumps.

De-aerators. The corrosive effects of hot water on boiler tubes, steam-pipes, etc., due to the presence of oxygen in the water dissolved from the atmosphere, has already been referred to. The

amount of oxygen that can be retained in solution is proportional to the partial gas-pressure and also depends inversely on the temperature of the water. Condensers act as de-aerators and reduce to a very low value the oxygen in the condensate and generally render the use of independent de-aerators unnecessary for many feed systems. To ensure that the percentage of dissolved oxygen in a system is a minimum, it is usual to install a de-aerator or de-gasser. De-aeration of feed water may be effected in a separate de-aerator placed in the feed system. By using a de-aerator the advantages of a closed system are obtained at reasonable cost. The de-aerator may be placed between the surge tank and the feed pump suction, the piping between the surge tank and the feed pump being maintained under pressure to prevent re-absorption of air by the de-gassed water. The solubility of air in water decreases with a rise in temperature and a reduction of pressure.

The principle on which the design of a de-aerator is based is that the amount of gas in solution in a body of water is proportional to the pressure of that gas in the water and on the surface of the water. If water is heated to boiling point, theoretically no gas can exist in the water or on the surface of the water, and any gases which were in the water should be driven out. Heating the water to boiling point will drive the gases out if sufficient time is allowed to elapse, but to obtain the desired effect in a reasonably short time in a plant of reasonable size it is necessary to subject the water to rapid and violent ebullation. The water is heated under vacuum and the heat required, in addition to removing the gases, increases the thermal efficiency of the system by imparting heat to the feed water.

The operation of three de-aerators are as follows :—

(1) Water is passed into a vessel in which a vacuum is maintained corresponding to the water temperature. By flowing either through a series of perforated trays or spray nozzles it is broken up into a fine spray, thus liberating a large proportion of the gases which are removed by an air ejector.

(2) Water to be de-aerated is passed through the top of a vessel in which a vacuum is maintained, and after passing through a series of perforated trays it falls over a bank of tubes arranged below to the inside of which steam is admitted. The temperature of the outer tube surfaces being higher than the temperature corresponding to the vacuum in the vessel causes the water to boil violently, breaking it up and liberating the dissolved gases which are extracted from the vessel.

(3) By allowing the dissolved oxygen to expend itself on specially prepared finely-divided steel (or iron) turnings loosely packed in a vessel. The water flow can be periodically reversed so that the faces of the metal are alternatively oxidised and rested. Periodical cleaning removes the iron oxide formed.

During the period of rest the film of oxide becomes loose and may be detached by the turbulent action of a steam ejector. Before leaving the vessel the water passes through a filter which retains the oxide.

A de-aerator can be installed in a feed system as a heater and has the additional advantage that all the drains from heaters at higher pressures can be led into the de-aerator where the total heat of such drains is conserved in the feed water without any further loss. A de-aerator of the third type is placed between the feed-pump discharge and the economiser. In other layouts the raw water to be evaporated is passed through primary crude water heaters before entering the de-gassers, the level of the water in the latter being controlled by means of a ball valve. A pump is provided on each de-gasser for extracting the water and discharging it through a secondary crude water heater to the evaporating plant. The pump should be corrosion resisting, and an air pump should also be included. The de-aerating plant may be placed near the feed heater or the evaporating plant, depending on its position and type adopted.

In the de-aerator used in one large power station having 60 MW sets the conditions favourable to gas-liberation are obtained by raising the feed water to a temperature of the steam atmosphere through which it falls. At the same time a large quantity of steam is passed through the de-aerator shell greatly exceeding that required for merely heating the water. As the boiling point of the water corresponding to the pressure is reached, the dissolved gases are driven out of solution into the current of steam passing over the surface of the water and ultimately pass to the condenser steam-space from which they are ejected by means of the air-ejectors. The de-aerating heaters are of the contact type. The complete de-aerator of each unit consists of a de-aerator chamber proper, a reservoir tank mounted below and connected to the base of the de-aerator chamber and a vapour condenser. The de-aerated water falls to the storage tank below, which serves as a reservoir on the suction side of a lift pump that delivers the de-aerated feed to the first high-pressure heater. The surplus vapour from the de-aerator chamber passes with the incondensible gases liberated to the vent-condenser through the tubes of which the water-supply to the de-aerator passes, thus it serves as a water pre-heater and air concentrator. The vapour condensed in this process is drained back to the base of the de-aerator, while the incondensible gases are passed to the main condenser.

The Weir Optimum De-aerator is illustrated in Fig. 371. The water enters A under the control of the float-operated valve B and is sprayed by the nozzles E into the top of the chamber D and falls into the compartment F. It then passes through the port G into the compartment H, where it is subjected to a rapid and

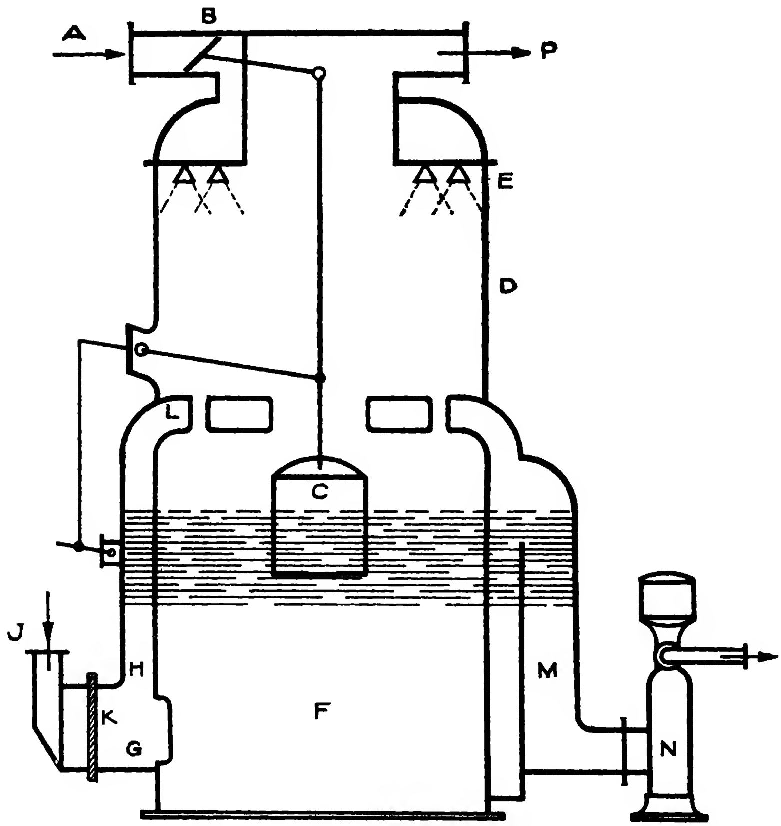


FIG. 371. Weir Optimum De-aerator.

violent boiling action by the admission of low-pressure steam which enters through the branch J and is distributed by the perforated plate K. The steam generated passes upwards through the ports L and is condensed by the cold spray from the nozzles E. The spraying and preliminary heating in the chamber D liberate the greater portion of the gases in the water and the final de-aeration is effected by the violent boiling in the compartment H. The gases

liberated are withdrawn at P by an air ejector or a vent connection to a condenser. The de-aerated water passes round the compartment H, over the weir and descends the passage M to the suction of the extraction pump N. This de-aerator is efficient at low or high temperature, and its operation is automatic and stable under widely varying conditions of loading. De-aeration to the extent of 0·02 c.c. of oxygen per litre of water can be obtained at temperatures as low as 100° F.

Figures for a typical de-aerator extraction pump are :—

Head due to vacuum . . .	32 ft.
Static head (34 lb.) . . .	80 ,,
Pipe and valve friction . . .	8 ,,
	120 ,,
Less positive suction head	40 ,,
	80 ,,
Delivery at this head	660 g.p.m.

Fig. 372 shows of one type of plant. The recirculating connection enables plant to operate and maintain a low oxygen

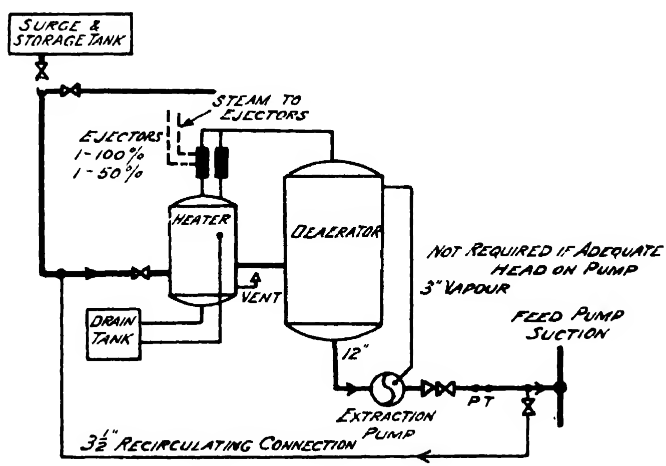


FIG. 372. 400,000 lb./hr. De-aerator.

content down to 70,000 lb./hr. The alternative is to fit nozzles to reduce capacity of plant to 150,000–200,000 lb./hr. although

this is not favoured, as a certain amount of spill over from valve would still occur, resulting in slightly higher oxygen content.

EVAPORATING PLANT

As pressures and temperatures continue to rise the necessity for pure distilled boiler feed water becomes more evident for wastage of fuel and the expense entailed by cleaning periods, apart from danger, etc., are factors of primary importance in any power station plant. Boiler heating surfaces which are entirely free from scale permit the highest possible rates of heat transference and long life of the tubes and drums is ensured by the absolute purity of the feed water and absence of corrosive conditions. With the high-pressure large capacity water-tube boiler the thinnest deposit of scale is dangerous to tubes as local heating and failures are sure to occur. Further, distilled water enables peak loads to be handled without danger of priming. Oil in feed water leads to scaling and should be carefully watched in all feed water systems. It may find ingress to the system by way of turbine glands and drains which are taken to a common drain tank. To determine the presence of oil in feed water use a clean test tube with a reasonable quantity of water to be tested and shake the tube for a few minutes, if at the end of this period there is no perceptible accumulation of oil globules then it may be considered free from oil.

The removal of the solid impurities in the make-up feed water is generally effected by evaporation. A given amount of condensate would circulate round the feed system indefinitely if it were not for leakage by drains, boiler blow-down, air ejector release pipe and evaporation. It is therefore necessary to provide a method of introducing a make-up supply of distilled water as required. This can be produced by vaporising in an evaporator, using as the heating medium high-pressure steam or low-pressure steam bled from a turbine. A central evaporating plant may be installed or each turbine may have an evaporator arranged for bled steam, the vapour produced in the evaporator being taken into a feed heater, where it is condensed by the feed water. The vapour or evaporate may be condensed in the main condenser but the heat in the steam is lost to the cooling water.

Another alternative is to exhaust into a suitable stage of the turbine, but there is a risk of water passing into the turbine in the event of evaporator priming. The general practice is to supply the evaporator with steam tapped from the same point on the turbine

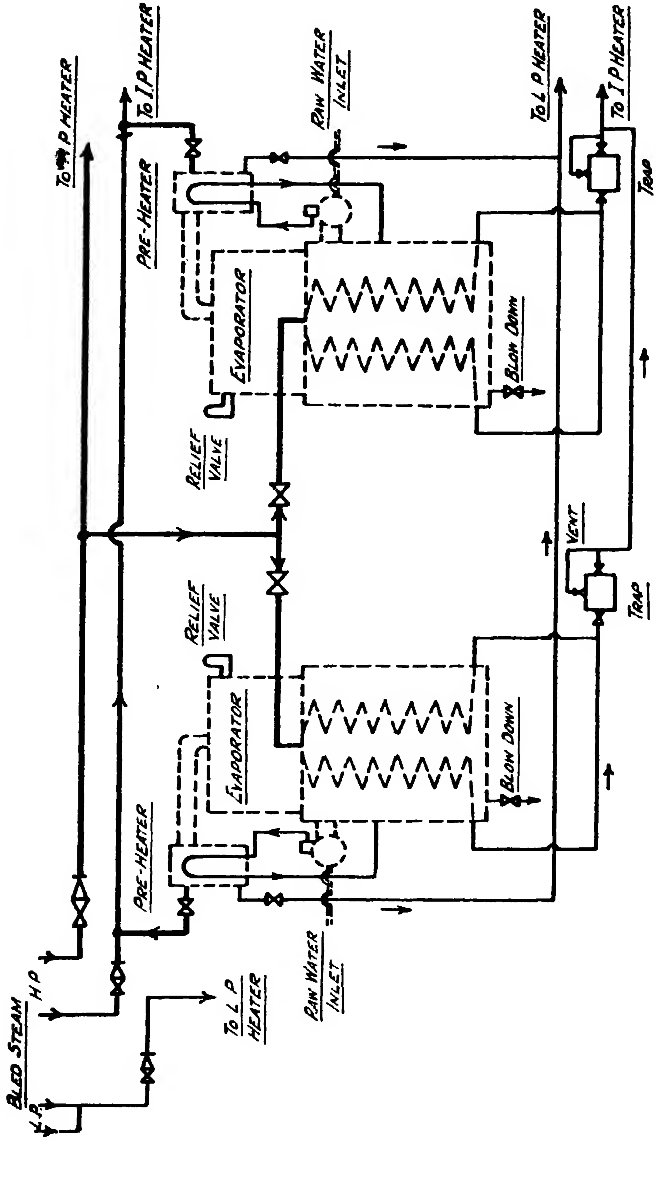


FIG. 373. Single-effect Evaporators for Large Turbine.

as one of the higher pressure heaters and condense it in the next lower pressure heater. The lower the evaporator steam supply the greater will be the thermal efficiency of the plant, but at very low pressure the cost of the evaporator is increased, also the cost of interconnecting pipework and valves due to the large volume of steam to be dealt with. Evaporators may be included in the feed system to operate between any desired temperature range, the usual drop allowed being about 60° F. with a single-effect evaporator to 100° F. with a double-effect evaporator. The choice of position of the temperature drop on the turbine temperature range is immaterial so far as the heat consumption of the evaporators is concerned because equal temperature drop corresponds to approximately equal heat drops throughout the region in which evaporators are usually fitted. A low temperature of evaporation is preferable because the solubility of most scale-forming solids increases as the temperature of the water is decreased and the precipitation of solids on the heating surface is thereby minimised. Calcium sulphate is the most troublesome impurity, since it forms a scale deposit which is crystalline, hard, compact and difficult to remove from the tube surfaces. Low-temperature evaporators are generally cheaper than high-temperature evaporators because the latter have to operate at higher pressures associated with high temperatures. A much larger heating surface may be provided in a single low-pressure evaporator than in a single high-pressure unit and while this advantage is slightly offset by the lower heat transmission rate available from the former, the difference is still considerable and allows a single-effect evaporator to be operated across a smaller temperature range. A low-temperature evaporator should have large steam areas which are essential for the passage of the low-pressure steam with a minimum loss of heat-head availability, and a large evaporating surface which ensures purity of distillate and permits of evaporation at heavy loads without priming. The heating surface may be based on a coefficient of heat transmission not exceeding 500 B.Th.U. per hour per sq. ft. of heating surface per °F. of mean temperature difference between the heating and heated mediums on full load. The duty of an evaporator is about 5 per cent. of the steam load but the make-up normally required is about 2 to 3½ per cent. The margin covers conditions when the evaporator becomes dirty and the duty is reduced, and allows a reserve of distilled water for boiling filling. For turbines of 30 MW and over it is usual to provide two half-capacity evaporators, so

arranged that one may undergo cleaning and maintenance while the other remains in service.

When the make-up is large or if the pressure of the available

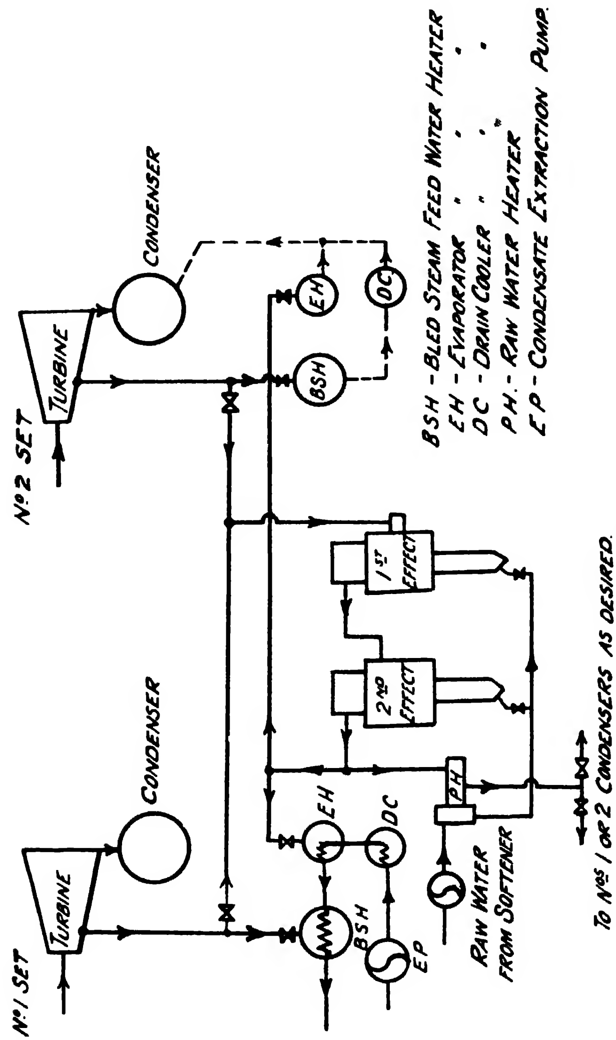


FIG. 374. Main Connections of Bled Steam Evaporator for use with Two Turbines.

heating steam is high, multiple-effect evaporators may be used. In this arrangement the evaporate from the first effect is used as the heating medium in the next and so on if more than two effects are used. Fig. 373 illustrates two single-effect evaporators and Fig. 374

shows an alternative arrangement. When operating with steam tapped from a turbine not more than two effects should be adopted, otherwise the temperature difference over each evaporator becomes small and the cost rises in proportion. The economy of the evaporator plant may be stated as the ratio of steam produced to steam used, *i.e.*, of secondary to primary steam. The amount of make-up produced by a single-effect evaporator is about 0·8 to 0·9 of the bled-heating steam quantity, whilst a double-effect evaporator produces about 1·5 to 1·7 times the bled-heating steam. The operation of an evaporating plant is simple, the level of the make-up in the evaporator being maintained constant by a float controlled admission valve whilst the output is regulated by a valve on the vapour discharge. The quantity of make-up vapour delivered by the evaporator is proportional to the pressure difference or gradient of the system, and as this gradient is a function of the load on the turbine the evaporator output is, for all practical purposes, directly proportional to total steam consumption of the turbine.

At very low loads it is possible for " carry over " to take place in the evaporator and cause contamination of the condensate. If a forced circulation type of evaporator is used the circulating pump glands will require sealing, the sealing water being taken from the extraction pump discharge or surge tank. This supply may be taken from the softener supply to evaporator and although the amount required for sealing is relatively small the contamination of the condensate is quite perceptible on the " Dionic " recorder at low turbine loads.

Evaporators may be of the coil-tube type or the straight-tube type. The former has the advantage that the tubes may be freed from hard scale by the process known as " cracking " without dismantling and withdrawing the coils. In this process the coils are first heated by means of a steam connection on the shell, and are then flooded as rapidly as possible with cold water, thus contracting the coils and cracking off the scale which is afterwards swept from the bottom through a mud-hole door.

Raw-water heaters are usually fitted to evaporators, their function being to heat the incoming raw water, using as the heating medium the drains from the steam coils or alternatively the evaporator vapour. By preheating the raw water the soft sludge is deposited in these heaters. This leaves the evaporator to deal only with the permanent hardness in the water and cleaning is reduced.

When a preheater is included the water should pass through the control valve before entering the heater as precipitation of sludge takes place on heating, which would result in the valve becoming choked if placed after the heater. If the evaporator operates with a vacuum in the shell a sludge pump or a steam ejector (trap) is fitted to withdraw the dense water and sludge from the bottom. The blow-down may be intermittent or continuous, the quantity depending on the hardness and amount of material in solution in the water supply. When installing such pumps the connections to the glands, suction and discharge circuits should be checked, otherwise trouble may be experienced.

The cost of evaporation should be ascertained when considering different types of evaporating plants. When comparing the steam consumption of different schemes for an evaporating plant it is necessary to evaluate the heat consumption of the evaporating plant in terms of boiler steam in order to obtain a true comparison. For this purpose the value of the heat leaving the evaporating plant must be deducted from the value of the heat supplied to the plant, the cost of evaporation being that amount of boiler steam which would give up the corresponding amount of heat if allowed to do work when expanding from the boiler pressure to the condenser. Assuming a turbine working at 600 p.s.i. gauge and 825° F., having an evaporator operating with bled steam at 52 p.s.i. absolute (approx.) in conjunction with a feed-heating system.

(*a*) The steam consumption of the turbine without the evaporator is 262,600 lb. per hour with a load of 30 MW.

(*b*) Steam consumption with evaporator is 266,900 lb. per hour.
Quantity of bled steam at 52 p.s.i. is 12,750 lb. per hour.
Evaporate produced is 12,000 lb. per hour.
Cost of evaporation = 266,900–262,600.
= 4,300 lb. per hour.

Evaporator produces $\frac{12,000}{4,300} = 2{\cdot}9$ lb. of distillate per lb. of boiler steam.

$$\text{Ratio of } \frac{\text{Secondary Steam}}{\text{Primary Steam}} \text{ or } \frac{\text{Steam produced}}{\text{Steam used}}$$

$$= \frac{12,000}{12,750} = 0{\cdot}94$$

With a double-effect plant the heat consumption would be nearly halved, *i.e.*, about 5·5 lb. of distillate would be produced per lb. of boiler steam but the capital cost of this plant is about twice that of a single-effect unit.

Another feature of interest in evaporating plants is the use of vapour compression which claims a high output per lb. of steam and simplifies the layout and arrangement of plant compared with multiple-effect evaporators. The compressor is simple, reliable, has no moving parts and its efficiency is higher than compressors of the jet type.

A diagrammatic arrangement of the plant is shown in **Fig. 375.** High-pressure steam admitted through (1) which draws into the thermo-compressor a quantity of vapour or evaporation by means of connection (2). The expansion of the live steam compresses the vapour sufficiently, so that when the mixture is discharged into the heating chamber through (3) its temperature is raised to give the

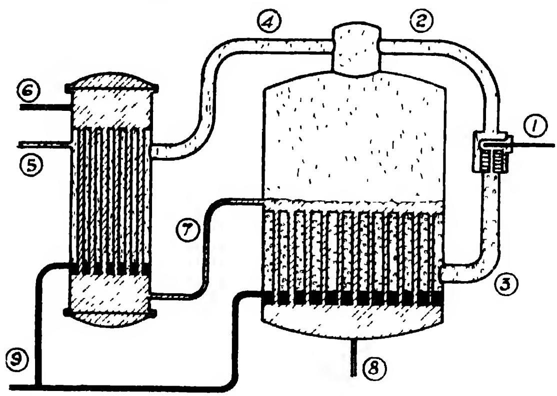


Fig. 375. Diagram illustrating Vapour Recompression Method of Evaporation.

1. Live steam to thermo-compressor.
2. Entrained vapour to thermo-compressor.
3. Discharge of vitalised vapour to heating chamber.
4. Excess vapour to preheater.
5. Vapour vent to atmosphere.
6. Raw water inlet.
7. Heated liquid to evaporator.
8. Extraction of concentrated liquid.
9. Extraction of condensate from heating chamber.

temperature head required for evaporation. The pipes collecting the distilled water are represented by (9). Vapour for heating the water in the preheater passes through (4), while the excess may go to the atmosphere by pipe (5), although provision is usually made to condense all the excess vapour. The raw water enters at (6) and the hot feed to the evaporator is at (7). The continuous extraction which is required to discharge scale-forming compounds and to keep the concentration from rising unduly is shown at (8). The

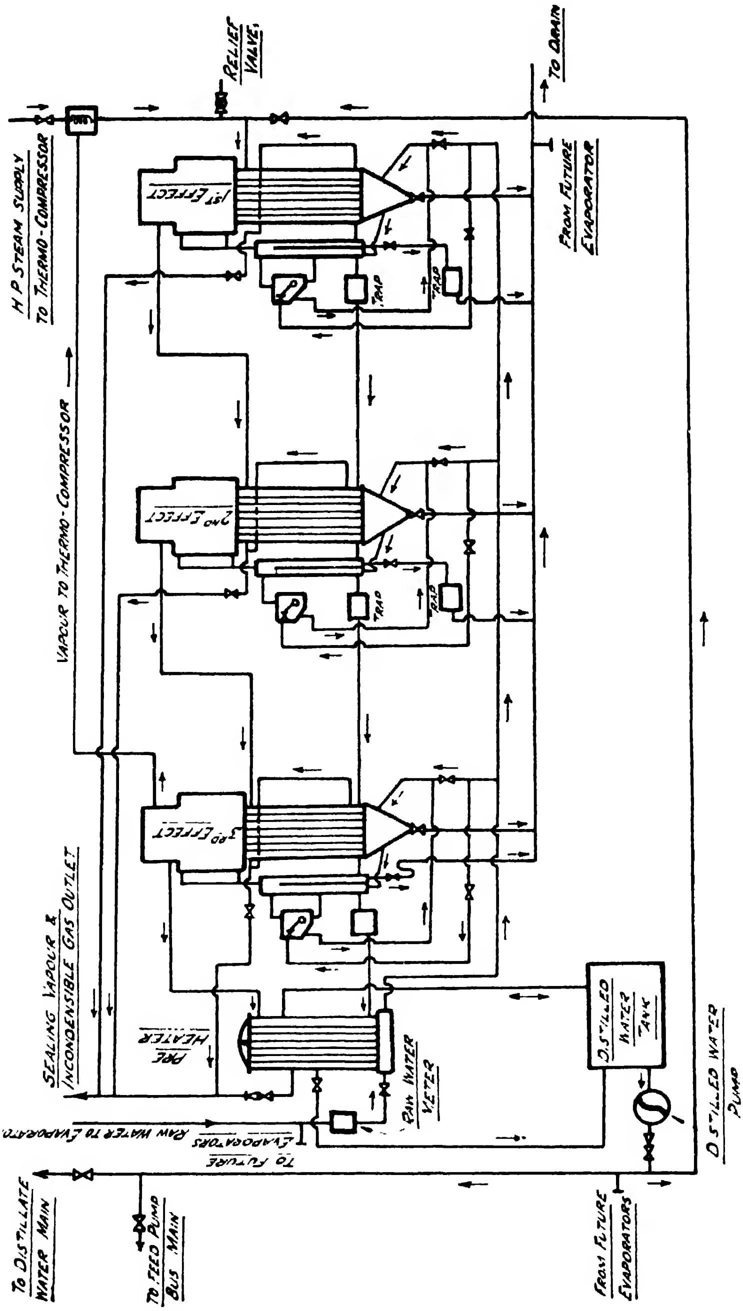


FIG. 376. Diagrammatic Layout of Central Evaporating Plant. (Aiton & Co. Ltd.)

constructional features vary in accordance with the working pressures and temperatures and the raw water to be treated.

The steam may flow through and the raw water outside the tubes, or the alternative arrangement is possible, depending on the type of plant used. The shell and collecting dome are of mild steel plate. The collecting dome or ebullition chamber is fitted with specially designed deflectors or baffles to prevent priming and ensure complete

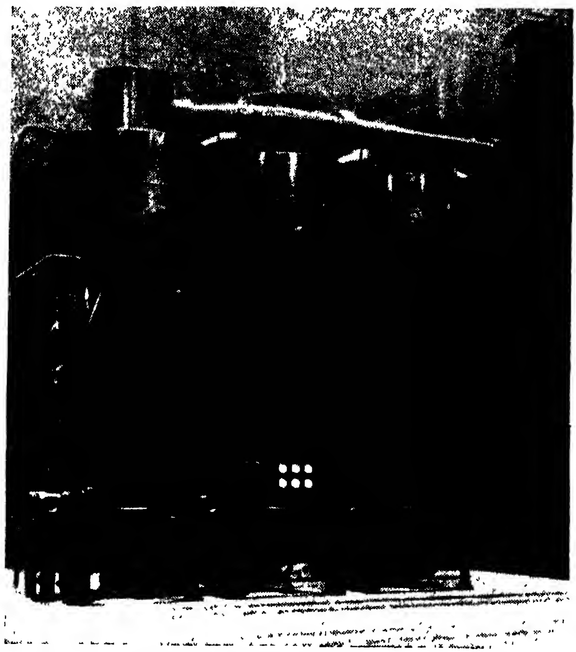


FIG. 377. Evaporating Plant, Kearsley Power Station. (Aiton & Co. Ltd.)

purity of the vapour produced. The tubes are of solid-drawn copper or alloy brass. When coiled tubes are used each tube layer consisting of two or more tube coils is separate and interchangeable, and is supported at the free end. The layers can be removed for cleaning purposes. The tube headers are of mild steel and the steam and drain headers of cast iron. Compound vacuum and pressure gauges are fitted on the steam and water spaces and an automatic feed water regulator, float traps, water-level gauge glass and relief valves are fitted. Evaporators are also used during shut down periods to maintain steam flow through the steam ranges to avoid

repeated heating and cooling with consequent joint failure due to condensation. Such an arrangement necessitates an increased distilled water storage and also slightly impairs the station thermal efficiency. Figs. 376 and 377 show two typical layouts.

WATER TREATMENT

The make-up water for boilers may be taken from a river, well or town main, the latter being probably the most expensive. The quality of this water is variable, depending on the locality, *e.g.*, it may form:—no deposit and be non-corrosive, much deposit and be non-corrosive, much deposit and be corrosive, no deposit and be corrosive. The necessity for treatment of make-up water will be appreciated from the notes concerning feed water. Internal corrosion in boilers and other plant in which water is heated may be due to one of the following :—

(1) Gases dissolved in the water.
(2) Acids present either naturally or from pollution.
(3) The corrosive mineral constituents in the water.

Examples of corrosion due to dissolved gases are chiefly met where the feed water is reasonably pure, *i.e.*, where the proportion of mineral constituents is small. The corrosion from dissolved gases may occur in either the steam or water spaces. In the water space it will usually occur where there is very little movement in the water or where there are projections on the surface of the metal on which bubbles of gas can lodge when liberated from solution by heat. Zinc slabs fastened in boiler drums reduce corrosion, the zinc being attacked and eaten away by the galvanic action of the corrosive agents instead of the boiler drums. An alkaline solution may attack evaporator copper coils and possibly brass and gunmetal nuts by alkaline boiler water. Copper is less resistant to caustic alkali than iron or nickel. By the concentration of base exchange treated water in evaporator heating chambers relatively strong alkaline solutions develop. Such solutions in the presence of organic matter (derived from peaty matter in town's main water, etc.) set up foaming conditions over which evaporator baffling arrangements have little or no control. Much has been written concerning caustic embrittlement. It appears that it is an actual physical change in metal that causes it to become very brittle and filled with minute cracks. It is believed to be caused by the action of caustic soda in boiler water, either naturally present or intro-

duced by some chemical treatment. The causes of caustic embrittlement are not definitely known. It does occur chiefly in riveted seams under rivet heads and is generally attributed to the presence of a high concentration of caustic soda, which results in an increase in static stresses and final cracking of the metal.

Water is referred to as being either " soft " or " hard." " Soft " water contains relatively small quantities of lime and magnesia salts in solution and " hard " water contains relatively large quantities of these salts in solution. A distinction must be made between " matter in solution " and " matter in suspension." The latter consists of mud and foreign particles which do not readily dissolve but retain a separate solid form and are easily detected by the eye. The hardness of water may be divided into two classes, temporary and permanent. Temporary hardness is that which can be removed by boiling and is caused by magnesium and calcium bicarbonates in solution. Permanent hardness is that which cannot be removed by boiling, and is caused by calcium and magnesium chlorides and sulphates in solution. These are stable compounds which are not affected by boiling, and to free water from these compounds distillation or chemical processes are necessary. The formation of boiler scale (Fig. 378) is due to the precipitation of calcium and magnesium salts and as boiler scale is a poor conductor of heat, the efficiency of a boiler which has " scaled " is impaired. Hard water in boilers not only produces scale, but may cause corrosion, foaming and bumping. To remove the hardening salts contained in water the soluble lime and magnesia salts are converted by chemicals into soluble salts, the lime salts into insoluble calcium carbonate and the magnesium salts into insoluble magnesium hydrate. To convert a soluble into an insoluble compound a definite quantity of another chemical must be added in order to bring about the change. If an insufficient quantity is added the trouble still exists, and if an excess is added the resulting state may be worse than the original. An efficient water-softening plant ensures that a given quantity of water receives a definite quantity of chemicals according to the amount of hardening salts present in the water it is required to remove and leaves no excess of added chemicals in the treated water. The cheapest and best chemicals available for softening water are lime (calcium hydrate) and soda ash (sodium carbonate). These are added to the make-up water in a proportion which by chemical analysis has been calculated to rid it of scaling and corrosive salts. The required proportion varies according to

the water used. Samples of the water should be tested by a chemist so that the hardness and chemical analysis may be obtained for submission to the plant manufacturer. Analysis should be made at regular periods as the hardness of the water may vary at different times of the year. This applies particularly to countries having rainy seasons. No matter how careful the treatment may be it is not possible to obtain perfect feed make-up water by chemical treatment,

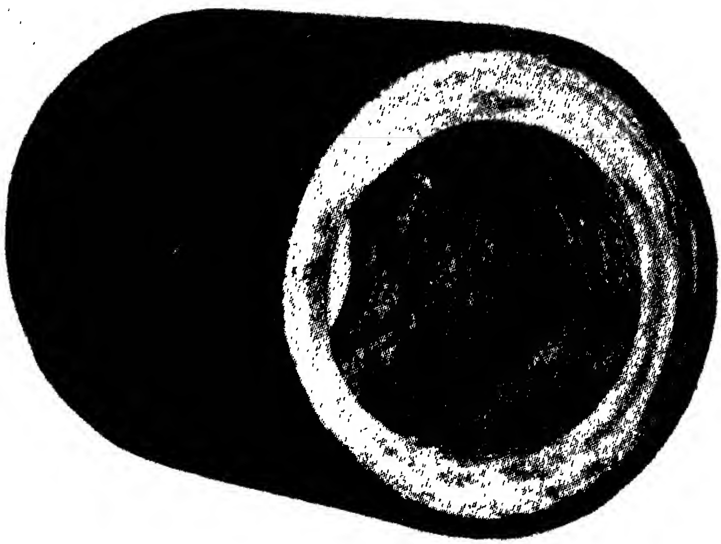


FIG. 378. Cross-section of Partially Choked Boiler Tube showing Deposit of Scale.

therefore distillation and de-aeration must follow this process. The distillation and de-aeration methods have been outlined. The make-up water is first passed through a softening plant before entering the evaporating plant. In one installation the water was reduced to 4° of hardness by passing through a softening plant. The original town water had a hardness of 20·5 parts per 100,000 of which 16 parts were represented by temporary hardness and 4·5 by permanent hardness. The water contained a small quantity of oxide of iron and peaty matter and had a *p*H value of 7·5, the quantity of water softening being 7,000 gallons per hour.

The chemicals required to soften this water were :—

Lime	$1\frac{1}{4}$ lb. per 1,000 gallons of water softened.
Soda ash . . .	$\frac{3}{4}$ lb. " " " " "
Sulphate of alumina .	$\frac{1}{4}$ lb. " " " " "

The softener was a Kennicott " K " type, the reaction chamber being 30 ft. high by 17 ft. 6 in. diameter, which gives to the water a full six-hour period for the chemical action to take place. The water to be softened enters the hard-water box and flows therefrom on to a water wheel. The water wheel in turn drives line shafting and, through bevel gears, a mechanical agitator rotating in the downtake of the softener where the chemicals and raw water are intimately mixed. An agitator also rotates in the chemical tank so that the chemical solutions are maintained homogeneously mixed. The sulphate of alumina proportioning gear consists of mild steel lead-lined dissolving and chemical tanks so that this coagulant may be proportioned separately from the lime and soda-softening reagent. An efficient wood wool filter is packed between two rows of perforated filter plates. The precipitated hardening salts which fall to the bottom of the main reaction chamber are extracted by means of a revolving sludging gear so that the plant is always maintained in a clean condition. The make-up supply from the town main is automatically shut off by an equilibrium float control valve operating from the level of the water in the softener so that if no water is being drawn from the softener, the float valve closes the inlet to the softener and automatically opens when water is taken from the plant. The softener is thus automatic in its operation. An automatic testing apparatus may be included to record continuously the hardness of the hard and softened water and the proportioning gear set according to its readings. Tests on both the hard and softened water are also made by the station chemist to check the recording apparatus. Figs. 379 and 380 illustrate the Kennicott water-softening plant.

In another installation of the Permutit Co.'s manufacture a base exchange process is used, the plant output being 2,000 gallons of softened water per hour. Some idea of the plant will be obtained from Fig. 381. Hard water is passed through a pressure cylinder containing base exchange material, which converts the lime and magnesium salts into sodium salts. After exhaustion of the bed of base exchanging material it is regenerated by a sodium chloride solution, which replaces the calcium and magnesium in the bed by sodium. The water to be handled in this case is taken from a river and the analysis of a typical sample is as follows :—

FIG. 379. Water-softening Plant, Dunston "B" Power Station.
(Kennicott Water Softener Co. Ltd.)

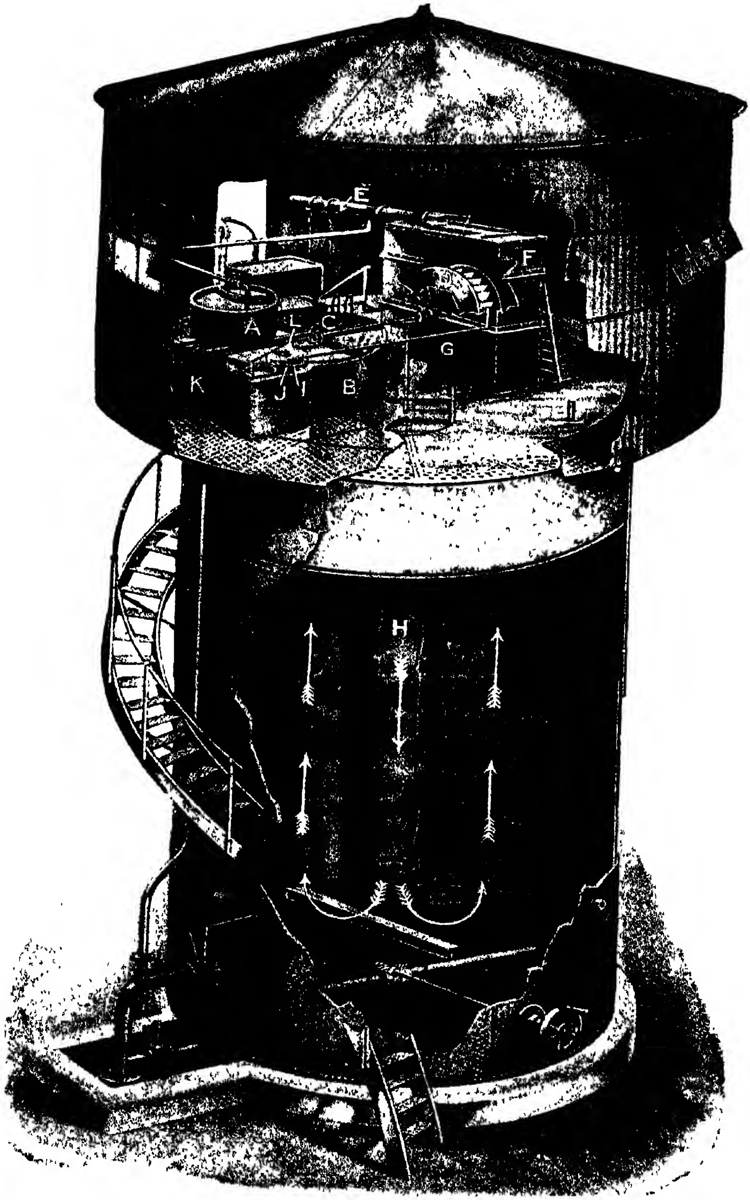


Fig. 380. Kennicott Type "K" Water Softener. (Lime and Soda Process.)

Condition at Time of Analysis

Appearance—almost clear.
Colour—Hazen 5.
*p*H value—7·6.
Suspended matter—2·0 parts per 100,000.

Analysis	*Parts per 100,000*	*Conventional Combinations*	
Lime (as CaO)	7·98	Silica	0·4
Magnesia (as MgO)	2·30	Calcium carbonate	14·25
Iron (as Fe) total	0·024	Magnesium carbonate	0·64
,, ,, filtered water	0·008	Magnesium sulphate	6·00
Silica (as SiO_2)	0·4	Sodium sulphate	0·25
Chlorides (as Cl)	3·55	Sodium chloride	5·85
Sulphates (as SO_3)	4·12		
Nitrates (as N_2O_5)	Nil		27·39
Free carbon dioxide (as CO_2)	0·4		
Dissolved oxygen	0·872		
Total solids at 180° C.	27·39		
Bicarbonate alkalinity (as CaO)	8·4		

Grains per gallon = parts per 100,000 × 0·7.

Temporary hardness	10·50°	English (grains $CaCO_3$)
Permanent hardness	3·50°	,, ,, per gallon
Total hardness	14·00°	,, ,, ,, ,,

Provision is made for dosing with alumina sulphate, the flow of chemical solution being added to the water by the differential pressure caused by a venturi tube in the water main, the flow being indicated by the chemical flow indicator on the water inlet line to the reagent container generator. The dosage is controlled by the regulating needle valve on the inlet side of the drip feed meter to 103 drips per minute, which is equivalent to a dosage of 2 grains per gallon. With this dosage the chemical drip feed meter will pass as denoted on the graduated scale 4,000 grains per hour with a flow of 2,000 gallons. The sand filter requires cleaning when the differential pressure as shown by the pressure gauge reaches 7 to 10 p.s.i. or when the flow is retarded due to the increased resistance of the bed. The steam-operated air injector is in service for about three minutes to agitate the filter bed with air. The water required for back flushing is about 160 gallons per minute. The capacity of the softening plant is 15,000 gallons between regenerations on 19·36° 'E.' The salt required is 78·75 lb. per regeneration, equivalent to 30 in. depth of saturated brine from measuring tank.

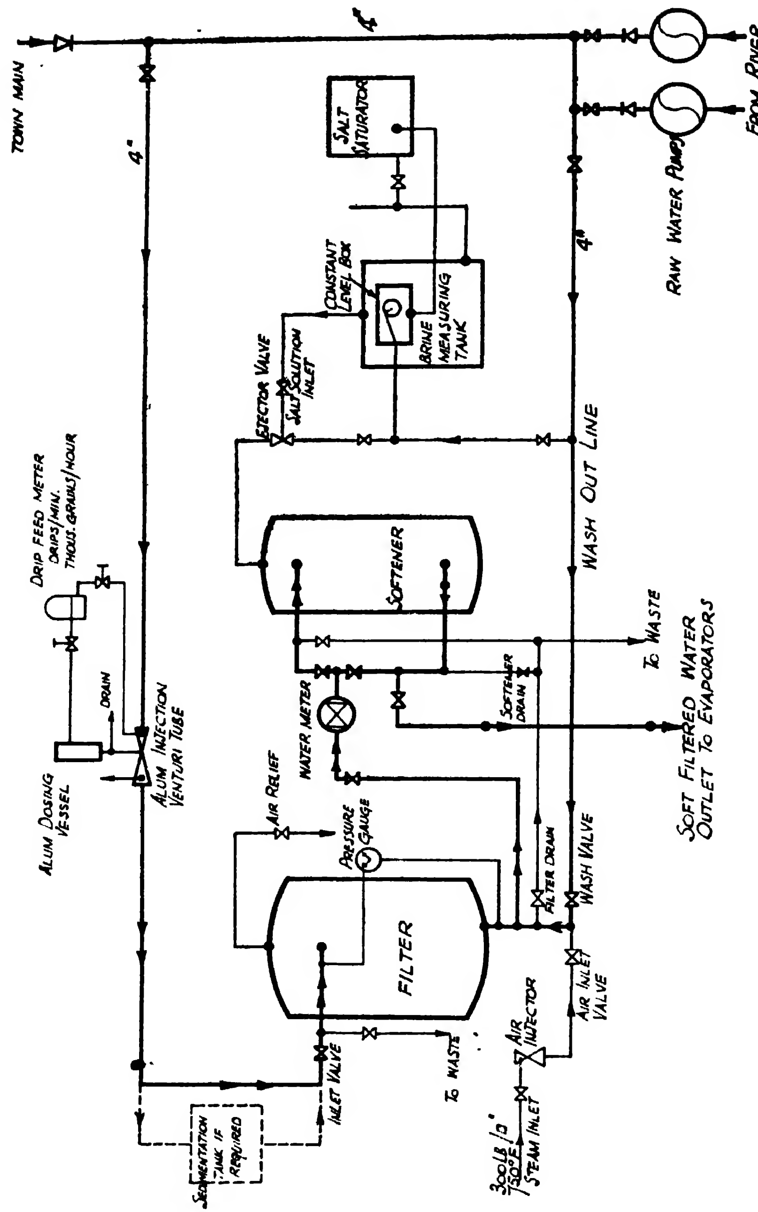
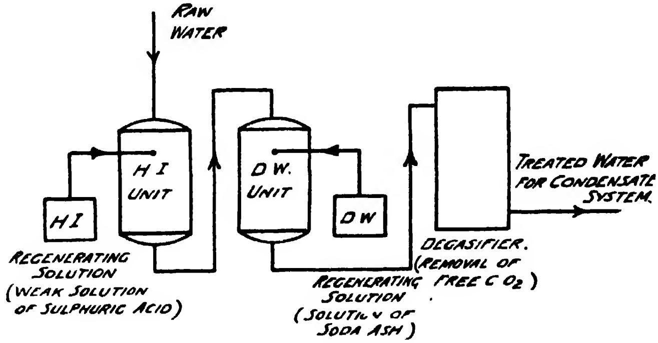


FIG. 381. Diagrammatic Layout of Water Treatment Plant. (Permutit Co. Ltd.)

The softener is back flushed prior to each regeneration for two minutes to loosen the bed and ensure proper contact with the brine solution. A prolonged back flushing is given according to working conditions. The back flushing is at the rate of about 29 gallons per minute. An open clean bed ensures the maximum yield of



H.I.—Hydrogen Ion Bed (Exchanging Plant)
D.W.—Acid Absorption Bed (Absorption Plant)
FIG. 382.—Demineralisation Plant.

softened water being obtained. Tests are taken to ascertain when regeneration is necessary.

Demineralisation Treatment. The "Deminrolit" (Fig. 382) process of water conditioning is also in commercial service and

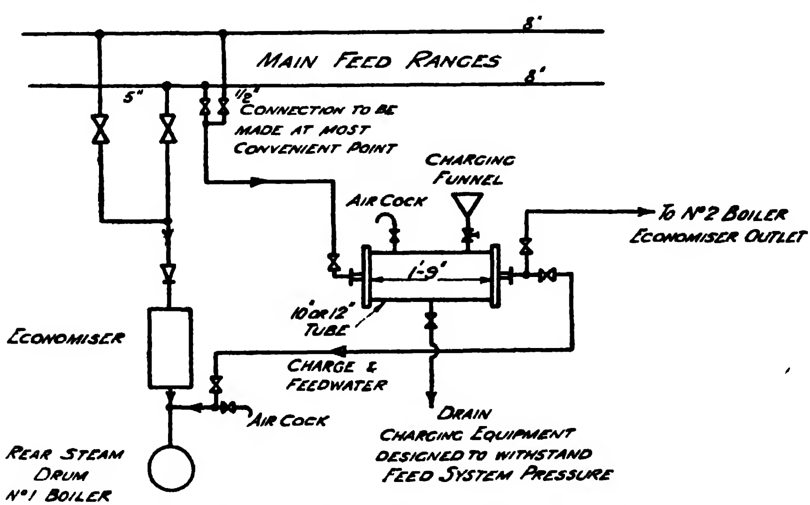


FIG. 383. Boiler Phosphate Charging Equipment.

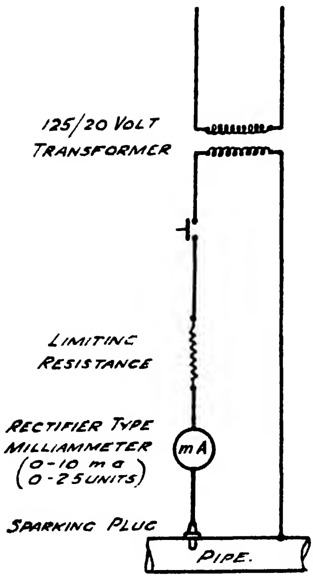


FIG. 384. Condensate Salinometer.

this method has the advantages of eliminating evaporating plant and is cheaper in capital and running costs.

Phosphate Treatment, etc. One method of introducing phosphate solution into the boiler feed system is illustrated in Fig. 383, where use is made of the pressure drop across the economiser. With phosphate treatment it is possible to have troubles from deposits in pipes, pressure-governing gear of turbo-feed pumps and de-aerator regulator controls. Such treatment removes tube scale, and after scale has been substantially eliminated the hardness of the boiler water becomes zero. Any departure from zero hardness means that the reserve of phosphate in the system has run short and that scale is liable to be deposited again. From 30 to 50 parts per million are

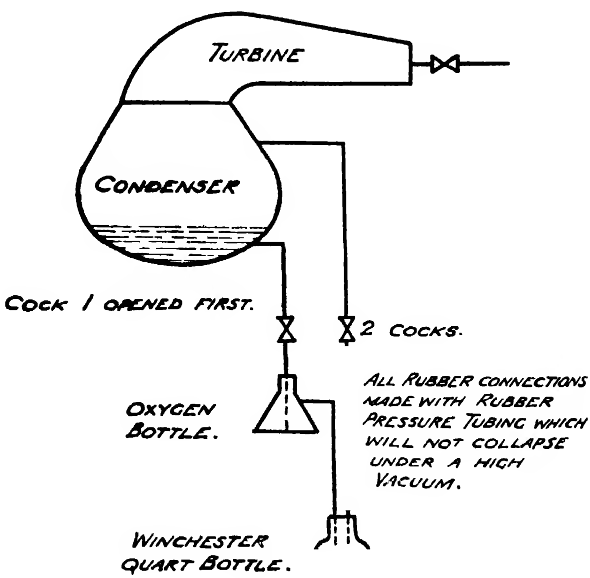


FIG. 385. Sampling under Vacuum for Oxygen Test.

general figures, measurement being made by colorimetric method in which reagents are added to a water sample. Cases are on record where trouble has been experienced due to corrosion of bronze impellers, etc., caused by the use of chemical treatment on the suction sides of the feed pumps. There has also been attacks on the bronze impellers in varying degree when the water to the pump has contained caustic alkalinity even where there has not been dry CO_3 present.

A simple condensate salinometer is shown in Fig. 384, and sampling connections for oxygen test are given in Fig. 385.

DROVE ROAD POWER STATION

CHEMICAL AND TESTING DEPT.

Week ending............................

WATER DATA

Boiler Water.

Boiler No.	*p*H.	Total Solids Grains/gall	Remarks.
1			
2			
3			
4			
5			
6			

The maximum permissible concentration bears a relationship to the working pressure, and the American Boiler Manufacturers' Association has suggested the following maximum values :—

Drum Pressure p s i	Total Solids in Water p.p m.
0– 300	3,500
301– 450	3,000
451– 600	2,500
601– 750	2,000
751– 900	1,500
901 -1,000	1,250
1,001–1,500	1,000

Another authority has suggested the following :—

Drum Pressure p.s.i.	Total Solids for Blowdown Control p.p.m.
0–250	7,000
251–500	5,000/2,000
501 and above	1,000

Condensate.

Turbine No.	pH (min.)	Dionic cond. (max.)	Remarks
1			
2			
3			

Circulating Water.

pH. (min.)	Dionic cond. (max.)	Remarks

Circulating Water System. Cooling tower systems are referred to in Chapter IV, Vol. I, and the question of make-up water reviewed. Water may be lime treated against the acid condition resulting from discharge of waste, etc., to river or canals. This water has a pH value of about 7 to 8 and is kept alkaline by adding suitable chemicals.

There are numerous methods of water treatment, some of which are the Spiractor, Spaulding and Santobrite.

The first method employs graded sand to cause the growth of the calcium carbonate crystals and lime is the only reagent used. The Spaulding process removes the temporary hardness by lime treatment alone.

Santobrite (sodium salt of pentachlorphenol) is a recent development for reducing algæ in cooling water systems and is an organic chemical in the form of briquettes which dissolve slowly in the water.

CHAPTER XII

ALTERNATORS

ALTERNATORS are of the rotating field type totally enclosed with "closed air-circuit" and may be either ventilated by means of fans on the rotor shaft or by separately driven fans. Probably the most outstanding characteristics of the turbo-alternator are its high speed of rotation and high voltage of generation. The present limits are 3,000 r.p.m. for sets up to 60 MW and a voltage of 36 kV. although the use of 66 kV. appears to be well nigh practicable. The rotors of the early high speed revolving field alternators were of the salient pole type but these were superseded by the cylindrical type of rotor. The power from alternators is transmitted over a fairly wide area either by the use of overhead lines or underground cables and under certain conditions of operation the load may therefore change suddenly in both magnitude and power factor. The alternators in conjunction with the exciters and automatic voltage regulators should be designed so that there is no undue rise in voltage at the power station in the event of the load being thrown off, assuming transmission lines still under full voltage and therefore drawing a leading current from the station.

A synchronous alternator performs two functions, namely, generating kilowatts (kW) and generating lagging kilovolt amperes (kVAr). Its output of kilowatts is controlled by adjusting the steam (or water, gas, etc.) supply ; increase of steam supply increasing the kilowatt output. Its output of kilovolt amperes (lagging kVAr) is controlled by the excitation ; increasing the excitation increasing the output of lagging kVAr. When an alternator is affording a supply of kW and lagging kVAr, e.g., to induction motors, it will operate at a lagging power factor. An alternator requires magnetisation in order to create its own flux ; it can only supply lagging kVAr to the electrical system if its excitation is increased above the value required to enable it to generate its own flux (over excitation). If its excitation is reduced below this value the required magnetisation needed to maintain its own voltage will have to be taken from the electrical system, i.e., from magnetising or lagging kVAr, supplied by other alternators on the electrical system. The alternator is then operating under-excited and will have a leading power factor.

Underground high voltage cables act as capacitors in parallel on the electrical system and may improve the power factor of the load to unity so that it does not require lagging magnetising kVAr to be supplied from the alternators. The necessary magnetisation is supplied by these capacitors as they act as alternators supplying lagging kVAr or in other words they absorb leading kVAr.

Methods of Rating. Two methods of rating turbo-alternators based upon temperature rise are adopted—the maximum continuous rating and economical rating. The maximum continuous rating indicates the highest loading at which the set may be run continuously, whilst the economical rating indicates a loading above which there is an overload capacity. The most economical output is not based on temperature rise and refers to the turbine or the combined unit. Particulars of turbine and alternator ratings are given in B.S.S. Nos. 132 and 225 respectively.

A typical specification clause is given :

"The alternator and exciter shall be capable of running at a continuous maximum rated output of 50 MW at any power factor between 0·8 lagging and 0·8 leading and also at an economical-rated output of 40 MW at any power factor between 0·8 lagging and 0·8 leading with a cooling air temperature of 40° C. without the temperature of any part attaining such a value as to affect the permanence and insulating properties of the winding and without the observable temperature rises in any part exceeding those given in the appropriate standard specification."

Power Factor. In fixing the kVA. rating of an alternator it is necessary to consider not only the kilowatt rating of the machine but also the probable power factor of the transmission or distribution system to which it is connected. Speaking generally 0·8 power factor will meet all cases. When designing an alternator for 0·8 power factor allowance must be made in the stator for 25 per cent. more current than would be required for unity power factor. Low power factor also affects the rotor design to a great extent, since the increase in rotor current and therefore the energy dissipated in heating the rotor coils is much more than the corresponding increase in the stator current. An alternator designed specifically for a load of unity power factor and utilising its full field capacity under that condition must not be loaded in kW. to more than 50 per cent. of its unity power factor rating if used on an 0·8 power factor load, otherwise the excitation will exceed the safe capacity of the field coils. Further, an alternator designed for 0·8 power factor may

show signs of instability if the load has a leading power factor. An alternator is usually designed to remain stable when carrying a specified kVA. at zero leading power factor.

Stator Voltage. For a given size of frame or rating of alternator there is an upper and lower limit of voltage for which the stator can be constructed. The reason is that when the voltage is very low the current is so high that large conductors and connections are necessary and when the voltage is high it becomes difficult to find sufficient room for the necessary insulation on the coils in the space available. Some idea of stator resistances will be obtained from the following :—

M.C. Rating MW	Voltage kV.	Resistance per Phase Ohms.	Temp. °C.
20	6·6	0·0037	15·5
30	33·0	0·041	,,

The choice of generation voltage was outlined in Volume 1, Chapter I. The increase in capacity of turbo-alternators together with the trend of distributing at relatively high voltage has given rise to the necessity of investigating the possibility of increasing the working voltage of these larger sets. In the majority of the present day stations the voltage varies between 6·6 kV. and 14 kV. although numerous machines have been operating at 20 kV. and 36 kV. for some years. These higher voltage machines have the advantages in that step-up transformers associated with lower voltage machines are eliminated and there is a consequent reduction in losses, saving in floor space and reduced fire risk. Further advantages are that the number of main cables required is reduced, and where the rupturing capacity of the existing switchgear is approaching the limit increased duty is not imposed on it. For some systems a fixed voltage is specified, *i.e.*, 6·6, 11 or 33 kV, but in some cases fairly wide voltage ranges are called for. Where the station busbars have reactors it is necessary to allow for the voltage drop under full load conditions. Apart from the question of cost it may be undesirable to specify any greater voltage range than is necessary. Operating at voltages below normal may affect the stability with a leading power factor since the alternator stability decreases when the field-ampere-turns are reduced.

To illustrate the justification of a high voltage machine the following example is given :—

Comparison of Costs of High Voltage and Low Voltage Alternators

	(*a*)	(*b*)
Alternator output	75 MW at 0·8 pf.	
Alternator voltage	11 kV.	33 kV.
Transformer losses (94,000 kV.A.). Fixed loss	150 kW.	—
Variable loss at rated load	500 ,,	—
Cooling plant auxiliaries	50 ,,	—
Annual cost of losses		
Basis—Capital charges	8 per cent. per annum.	
Fixed loss per kW.	£7 3*s*. per annum.	
Copper losses at full load per kW.	£2 per annum.	
Fixed losses (including auxiliaries)	£1,460	—
Variable losses	£1,000	—
Total annual cost of losses	£2,460	—
Comparison on capitalised basis.		
Approximate additional cost of alternator	—	£7,500
Cost of transformer	£15,000	—
Cost of cables	£3,000	£1,500
Additional cost of buildings and transformer foundations, etc.	£1,500	—
Capitalised value of transformer losses at 8 per cent.	£30,800	—
Total	£50,300	£9,000
Total per kW.	£0·67	£0·12

The capital saving in favour of a 33 kV. alternator is £50,300 − £9,000 = £41,300 or 11*s*. per kW.

These are pre-war costs.

Voltage Wave Form. The cylindrical rotor with its distributed windings has the advantage that the wave form of the stator voltage approximates closely to a sine wave both on open circuit and on load. The wave form between line and neutral should be sufficiently near the sine curve to restrict the circulating current to a reasonable value when the neutral is connected to earth. The alternator design should in no way appreciably interfere with any telegraph, telephone communication or signalling installations.

Regulation. Alternators with large internal reactance necessarily have a wide inherent voltage regulation. The inherent regulation of alternators was of importance in the early days in limiting variations of the voltage due to changes in the load. To obtain good regulation it was necessary that the demagnetising effect of the

armature (now stator) should be kept as low as possible. This demanded few turns on the armature which necessitated a large flux and a correspondingly large volume of iron in the alternator. With the development of reliable automatic voltage control equipment the need for good inherent regulation of an alternator is unnecessary. The trend in design has been to increase the number of turns on the armature, thus reducing the weight of iron. The inherent regulation for a typical 50 MW 11 kV. alternator is 41 per cent. at 0·8 p.f., 38 per cent. at 0·9 p.f., and 28 per cent. at unity p.f.

Reactance. By increasing the turns the self-inductance of the alternator windings is increased with consequent reduction of short-circuit current. A typical oscillograph record is shown in Fig. 386. The self-inductance is known as the inherent reactance

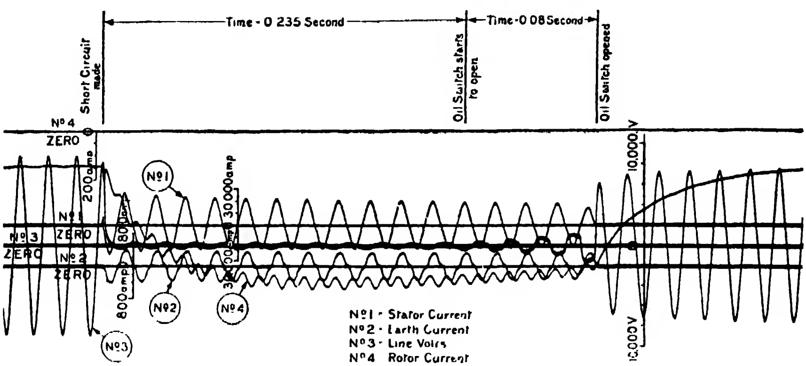


FIG. 386. Oscillograph Record taken on 40,000 kVA. Alternator subjected to Sudden Single-phase Line to Line Short-circuit when Running at Full Voltage. (British Thomson-Houston Co. Ltd.)

and is expressed as the percentage of the normal voltage required to circulate full-load current in the stator windings. The mechanical forces on the alternator windings due to the short-circuit current are less and the rupturing capacity of the main switchgear can be reduced if system conditions permit. The reactance of synchronous machines has been considered under three headings :

(1) Synchronous reactance or positive sequence which is divided into two components, one of which is the armature leakage reactance and the other the reactance of armature reaction, that is the demagnetising effect of the stator current.

(2) Transient reactance which is composed of the armature leakage and effective field leakage.

TABLE 49. *Turbo-Alternator Reactances*

kVA rating . . .	15,000	25,000	37,500	37,500	62,500
Voltage	11,400	6,600	11,400	33,000	11,400
Speed r.p.m. . . .	3,000	3,000	3,000	3,000	1,500
Direct axis. Transient reactance per cent. . .	20·6	17·0	24·7	27·0	23·0
Direct axis. Sub-transient reactance per cent. . .	13·75	12·5	15·7	20·0	15·0
Synchronous impedance per cent.	101·0	255·0	195·0	280·0	145·0

(3) Sub-transient reactance which takes into consideration the effect of damper windings on the short circuit current.

The stator of an alternator possesses only one real reactance, that is the leakage reactance due to the lines of force which link the stator winding alone when a given current is passed through it. In the case of an alternator with an efficient rotor damping winding this reactance may be measured by withdrawing the rotor, passing the normal full load current at the rated frequency through the winding and measuring the phase voltage drop.

Let I_{FL} be the full load current.
E_X ,, ,, ,, phase voltage drop.
X_L ,, ,, ,, leakage reactance per phase,

then
$$X_L = \frac{E_X}{I_{FL}} \text{ ohms.}$$

or, expressed as a percentage :—

$$e_L = \frac{X_L \cdot I_{FL}}{E_N} \cdot 100.$$

where E_N is the normal phase voltage.

e_L = leakage reactance per phase, per cent.

When the alternator is on load the e.m.f. generated by the main flux of the rotor must overcome the external load impedance and the leakage reactance. If an alternator is running fully excited on no load and it is suddenly short circuited the full voltage acts

round the circuit formed by the short-circuited winding, the only impedance in which is the resistance of the winding (almost negligible) and the leakage reactance. The current that flows is given by dividing the no-load voltage by the leakage reactance (X_L) as ascertained above. The presence of the rotor inside the stator only very slightly reduces the current as the leakage flux from the stator is confined to the outermost layer of the rotor by the presence of the damping winding in the upper part of the rotor slots. What is usually known as the "instantaneous" short-circuit current then flows, the value of which may be from 5 to 10 times normal full load current depending on the design. As soon as the short circuit begins to flow the armature reaction acts upon the flux which is more or less gradually reduced until it reaches a steady value. Armature reaction is only of importance when the short circuit is at or near the alternator terminals. This data is useful in connection with overcurrent protection for alternators.

The reduction of the flux results in a reduction of the generated e.m.f. and therefore in a diminution of the current until the "steady short circuit" is reached. The value of this depends upon the value of the excitation current but for an excitation current corresponding to the full-rated capacity of the alternator it is about $1\frac{1}{2}$ to $2\frac{1}{2}$ times normal full-load current. In practice only the "transient" and sub-transient components are recognisable. The transient reactance is that value in ohms which when divided into the normal full load voltage gives the initial instantaneous value of the component of the total short circuit current which has the largest time constant. The transient time constant is the time constant of the transient short-circuit current. The "sub-transient" reactance is similarly that reactance which when divided into the rated phase voltage gives the total initial short-circuit current, *i.e.*, the transient component plus the sub-transient component which is superimposed. The sub-transient reactance is thus less than the transient reactance (Table 49). The synchronous impedance is based on the air line characteristics, *i.e.*, does not include the effect of any saturation in the iron. The sub-transient time constant is the time constant of the small, rapidly disappearing sub-transient component of flux or current, while the transient reactances may be used to define the transient components of the short-circuit current, the "synchronous reactance" may be used to calculate the steady short-circuit current. It is that value in ohms which when divided into the phase voltage gives the steady short-circuit current.

In this country the reactance of an alternator refers to the sub-transient reactance. If an alternator has a reactance of 20 per cent. it is understood that if it is short-circuited when fully excited the instantaneous initial value of the short-circuit current (neglecting asymmetry) is $\frac{100}{20}$ times normal full load current. The only use of the terms transient and sub-transient reactance is to enable one to define the shape of the curve corresponding to the gradual disappearance of the flux and consequent diminution of the short-circuit current. The sub-transient reactance obtained from a number of three-phase sudden short circuits at full voltage (30 MW, 33 kV.) was about 18·5 per cent.

Referring to Fig. 398, the synchronous impedance of an alternator can be estimated from the open circuit (saturation) and short-circuit (impedance) characteristics as follows :

$$\frac{\text{Stator E.M.F. on open circuit}}{\text{Stator Current produced on short circuit}},$$

both for the same value of excitation current.

Assuming an excitation current of 100 amps.

Stator open-circuit voltage = 9,000 volts.

Short-circuit current = 4,800 amps. (approx.)

16 per cent. reactance assumed.

The synchronous impedance $= \frac{E}{I} = \frac{9{,}000}{4{,}800} = 1{\cdot}87$ ohms.

The alternator output at this current $= \frac{9{,}000 \times 4{,}800 \times \sqrt{3}}{1{,}000}$

$= 75{,}000$ kVA.

The impedance voltage = 9,000.

Expressed as percentage of working voltage $= \frac{9{,}000}{11{,}000} \times 100$

$= 82$ per cent.,

and the short-circuit kVA. of the alternator $= 75{,}000 \times \frac{100}{82}$

$= 91{,}500$ approx.

This method of estimating synchronous impedance (or reactance, since resistance may be neglected) assumes that the alternator operates in an unsaturated condition. Such is not the case as is shown by the bend in the curve and the results are therefore only

approximate. As a guide a few typical examples are given in Table 49.

CONSTRUCTIONAL DETAILS

Stator. The stator casing is built up of fabricated steel plate, electrically welded. A stronger yet lighter construction is obtained compared with cast iron and, further, the risk of hidden flaws is eliminated. The core is built up of stampings of high permeability, low hysteresis and eddy current losses. Eddy currents are minimised by coating the laminations on each side with an enamel which is afterwards stoved. Radial ducts are provided at regular intervals throughout the length of the core to ensure efficient cooling of the

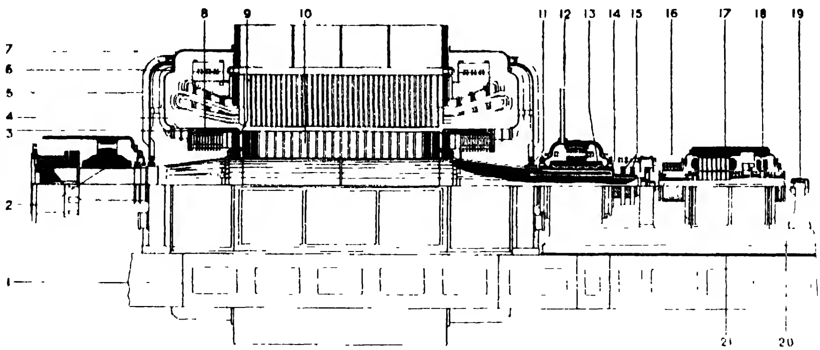


FIG. 387. Half Sectional Elevation of a Typical B.T.H. 1,500 r.p.m. Turbo-alternator and Exciter.

(1) Alternator Baseplate.
(2) Alternator Centre Bearing.
(3) Rotor End-flange.
(4) Fan.
(5) Air Shield.
(6) End Shield.
(7) Winding Cover.
(8) Rotor Retaining Ring.
(9) Rotor Support Plate.
(10) Rotor Cone Plate.
(11) Air Baffle (Spring Type).
(12) Oil Vent Pipe.
(13) Outboard Flexible Bearing.
(14) Oil Thrower and Oil Guard.
(15) Slip Rings.
(16) Exciter Flexible Coupling.
(17) Main Exciter.
(18) Service Exciter.
(19) Exciter Outboard Bearing.
(20) Alternator Pedestal Base.
(21) Insulating Shim.

stator iron and the embedded portion of the stator windings. Half-sectional elevations of turbo-alternators are shown in Figs. 387 and 388.

Core bolts passing directly through the laminations are not used since it is possible for these to become a source of danger due to heating set up through circulating currents. To ensure a tight core the laminations are assembled in stages of about 2 ft. and at

each of these stages the core is clamped under heavy but uniform pressure.

The stator windings are usually one of three main types :—

(1) Diamond coil winding.
(2) Concentric coil winding.
(3) Involute coil winding.

The first type is sometimes referred to as the basket, barrel or double layer winding, the end coils being of basket form. In this stator winding the stray magnetic field produced is small and stray losses due to eddy currents induced in adjacent parts are therefore low. For the same reason the magnetic forces on the windings in the event of a short circuit are also low. The coils being similar in shape and dimensions require a minimum of spares, and heavy clamping

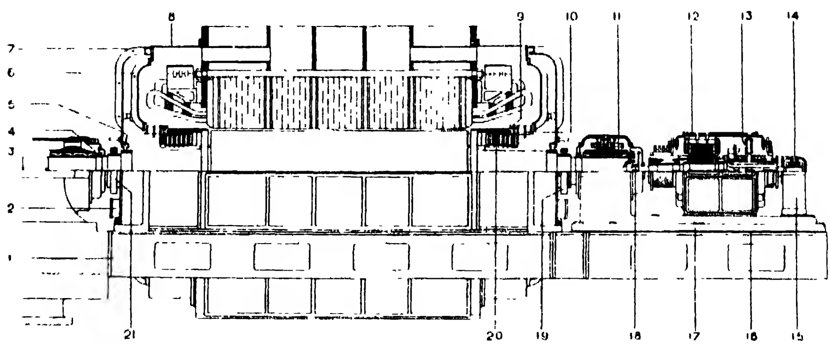


FIG. 388. Half Sectional Elevation of a Typical B.T.H. 3,000 r.p.m. Turbo-alternator and Exciter.

(1) Alternator Baseplate.
(2) Aspirator.
(3) Alternator Centre Bearing.
(4) Oil Thrower and Oil Guard.
(5) Air Baffle (Spring Type).
(6) End-shield.
(7) Air-shield.
(8) Winding Cover.
(9) Rotor End-flange.
(10) Fan.
(11) Outboard Flexible Bearing.
(12) Main Exciter.
(13) Service Exciter.
(14) Exciter Outboard Bearing.
(15) Exciter Bearing Pedestal.
(16) Insulating Shim.
(17) Alternator Pedestal Base.
(18) Exciter Flexible Coupling.
(19) Slip-ring.
(20) Rotor Retaining Ring.
(21) Slip Ring.

bolts are eliminated. In the second type the stator core conductors and the end connections are separate. Semi-enclosed slots may be used and the possibility of introducing ripples in the voltage wave form is minimised. Eddy current losses in the surface of the rotor are also reduced. A higher reactance may be obtained with a semi-enclosed slot than with an open slot of similar dimensions.

each circuit is brought out separately so that a suitable scheme of protection can be included. The method of bringing the connections to the sealing ends depends on the design and layout of the alternator and its foundation block. If cables are used provision should be made for supporting and accommodating the sealing ends. With copperwork, supporting insulators are necessary. The current transformers associated with the protective apparatus also have to be accommodated, and this entails a chamber in the foundation block. This chamber may have a wire mesh, asbestos or steel plate door with holes and bushes for the exit of cables. When the last two types are used they should be lightly fixed so that they are readily blown off in the event of an explosion in the chamber caused by flash-over or failure of insulators. Defective steam and water pipes in the vicinity have to be guarded against and the possibility of damage from blast and splinters must also be kept in mind.

The copper connections are brought from the alternator through insulating bushes placed in a dividing wall and then to the sealing ends (Figs. 391 and 392). Copperwork in the form of strip and tube mounted on insulators has been used to connect the main step-up transformer, which may be some 50 ft. or more away from the alternator connections. Where the current is reasonably low as in 20 kV. and 36 kV. alternators, copper rod may be used. One 30 MW —33 kV. turbo-alternator connection was made from $\frac{7}{8}$ in. diameter copper rod insulated with mica silk to a radial thickness of $\frac{1}{4}$ in., whilst in another $1\frac{1}{4}$ in. diameter copper rod insulated with layers of bitumastic silk Empire tape (22—$\frac{1}{2}$-lap layers) was used. Each layer may be treated with bitumen brushing varnish and a final layer of half lap adhesive tape given a coat of finishing varnish to ensure a smooth finish. The connections are fully insulated at the works and given a flash test of 33 kV. for one minute. Wherever copperwork is used it should be insulated to withstand full-line voltage as cases are on record where flash-over has taken place due to a polluted atmosphere or vermin, *e.g.*, air-cooler leakage, salt laden atmosphere, burst steam or feed pipes, rats, etc. If bare copperwork is used care should be taken in the design, construction and layout of the connections to avoid the formation of ozone. Hard-drawn copper is used and all contact surfaces cleaned by dipping after machining, the machined surfaces having a perfectly smooth finish to ensure good electrical contact. In one station a severe flash-over took place across all phases in the sealing end and current transformer chamber, resulting in the destruction of six of the sealing

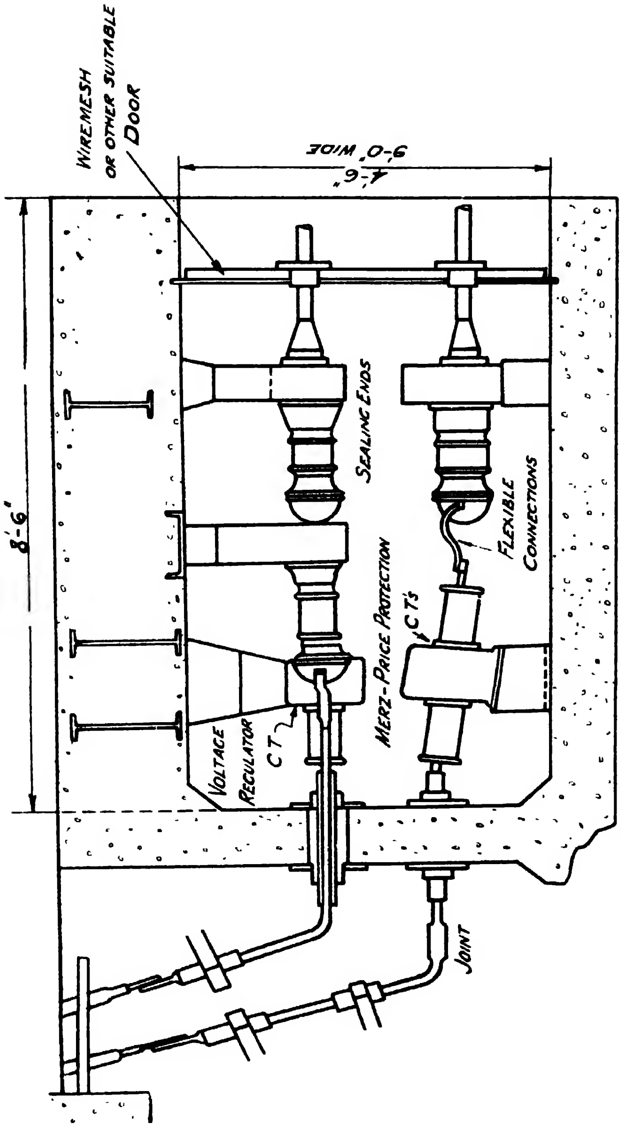


FIG. 391. 30 MW—33 kV. Turbo-alternator Main Connections.

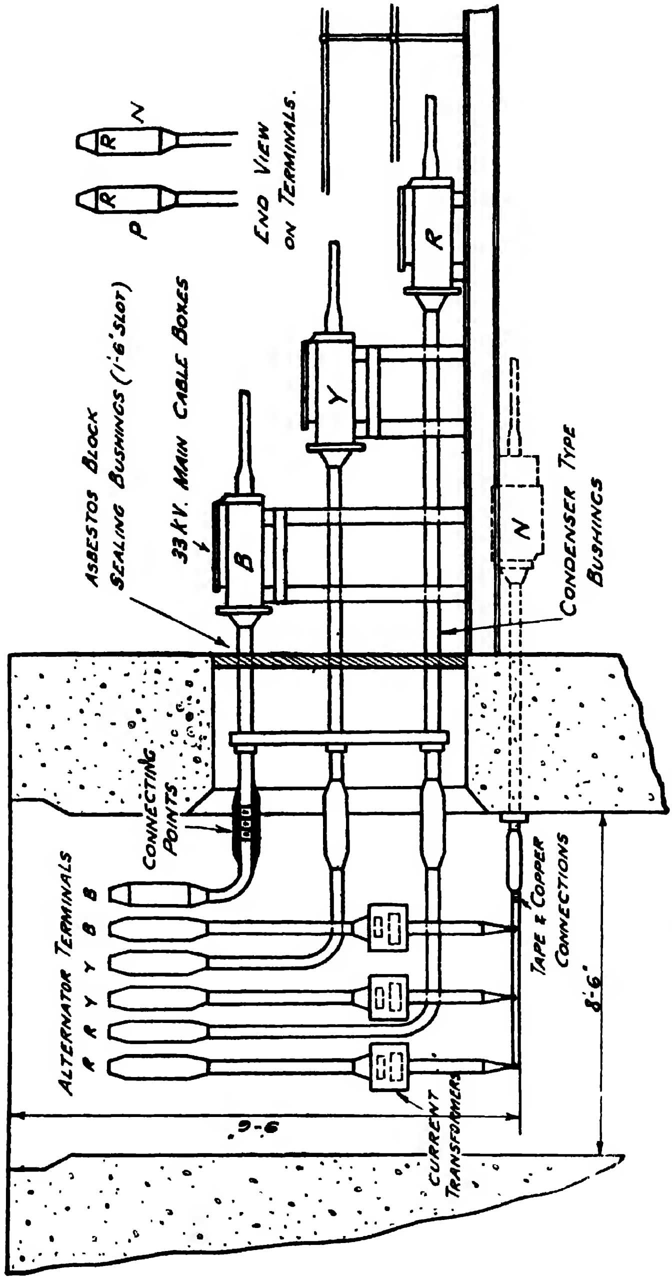


FIG. 392. Alternator Main Connections with Condenser Type Bushings.

ends and extensive burning of the copper connections. The flash-over was due to the air in the chamber becoming laden with moisture caused by a defect in the air-cooler resulting in the porcelains being covered with a moist film. The design and arrangement of the alternator air-cooling system should be such that the current transformer and sealing end chamber is completely sealed from the air circuit to prevent damage in case of cooler leakage. This is accomplished by the inclusion of a concrete dividing wall through which the leads are taken and afterwards sealed. In the event of short-circuit on the system—especially on the connections between the step-up transformer and the alternator—these connections and bus-bars are subjected to high electromagnetic forces. The design, layout and general construction of the bus-bars and their supports should be such that they are mechanically strong to enable them to withstand all stresses due to fixing, vibration, temperature changes and short-circuits. The bare copper bus-bars are sometimes supported on insulators in concrete chambers with concrete barriers between phases and in this way electrical and physical separation is obtained.

Laminated strips of electrolytic copper are used, but tube and rod have been used to advantage. Typical fixing details are given in Table 50.

TABLE 50. *Bus-bar Details*

Size of Strips (ins.)	Size of Bolts (in.)	Number of Bolts
1×1	$\frac{3}{8}$	1
$1\frac{1}{2} \times 1$	$\frac{1}{2}$	1
2×1	$\frac{3}{8}$	2
$2 \times 1\frac{1}{2}$	$\frac{3}{8}$	2
2×2	$\frac{3}{8}$	4
3×1	$\frac{1}{2}$	2
3×2	$\frac{3}{8}$	4
3×3	$\frac{1}{2}$	4
4×1	$\frac{1}{2}$	2
4×2	$\frac{5}{8}$	2
4×3	$\frac{1}{2}$	4
4×4	$\frac{5}{8}$	4

The recommended electrical clearances for both indoor and outdoor are given in B.S.S. 162/1938.

Provision should always be made, even in short connections, for expansion and contraction of the copperwork so that no undue mechanical stress is imposed on the insulators and supports. When expansion joints have to be introduced they are usually made up of a number of copper laminations of 0·01 in. thickness, this form being preferred to solid pieces of soft copper, as the latter tends to harden with repeated expansion and contraction. If cable boxes with condenser type bushings are used expansion is provided by winding them in such a manner that about one-third of the conductor length is anchored to the insulation, the remainder being free to expand. Another problem relating to the design of bus-bars is that of heating, and the requirements are set out in B.S.I. Specification 159—1932. Probably the best design for open bus-bars is obtained by selecting wide thin strips of copper and having as few as possible. Where cables are employed these will also be subjected to the magnetic forces referred to and single-core cables should be supported on racks and have intermediate clamps at regular intervals. If these precautions are not taken the cables may be distorted during short-circuit and be rendeoed unfit for further service.

Terminal Markings. The phase sequence and terminal markings should always be given. If there is any particular manner in which the terminals are required to be taken out this information should be available to the alternator manufacturer at an early date. This applies in particular where copper bus-bars are to be used, since it is difficult to introduce a cross-over. With single-core cables this is simple but should be avoided if possible. In some cases step-up transformers have had to be connected non-standard to avoid a cross-over in the copperwork from the alternators. Fig. 393 indicates cross-overs necessary. In a three-phase turbo-alternator the disposition of the stator windings and the direction of rotation of the field system (rotor) will determine the order in which the induced voltages attain their maximum values. These conditions being fixed, the system then has an inherent phase sequence or order in which the phase voltages rise to their maxima and if the phase windings are denoted by figures or colours the phase sequence may be given an arbitrary representation. The generally accepted standard-phase rotation is red, yellow and blue—rising in that order—the non-standard being red, blue and yellow. This method of representation may then be applied to the convention of showing the maximum phase voltages by three vectors 120° apart. The instantaneous value of each phase voltage is given by the projection

of each vector on the vertical line AB in Fig. 394, and if the values are attained in the order R, Y, B, R the three vectors may be considered as revolving in space in a counter-clockwise direction, which is the standard conventional direction of phase sequence. Alterations

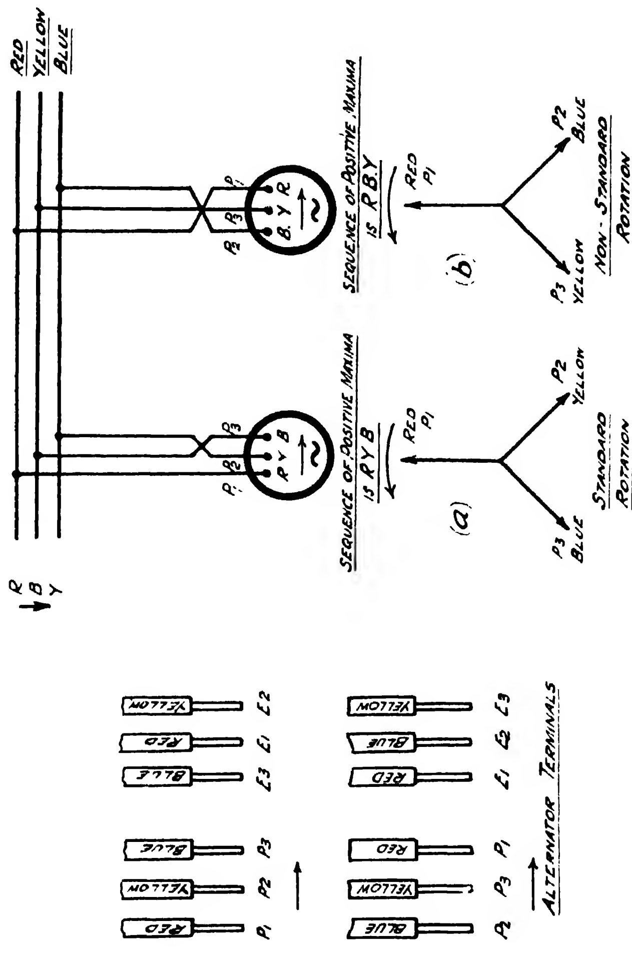


FIG. 393. Alternator Connections and Phase Sequence Diagrams.

in the phase rotation and terminal colouring will necessitate change-over of current transformer connections so it is desirable to ensure close co-operation between the switchgear and turbo-alternator contractors. The accuracy of metering equipment is affected by change of phase rotation.

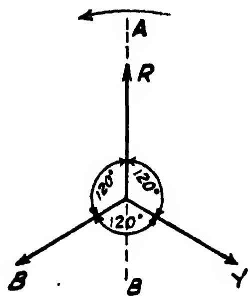


Fig. 394. Standard Phase Rotation.

The connections may be checked on site if desired, but generally speaking they are usually correct. The rotor may be excited from a D.C. supply (5 to 10 amps.) and given a spin in the normal direction of rotation by means of the overhead crane, a phase rotation indicator being connected across the stator terminals colour to colour.

The following example shows the method of estimating the short-circuit forces on alternator and similar connections.

A 50 MW turbo-alternator operating at a power factor of 0·8 has a terminal voltage of 13·5 kV. and reactance 15 per cent. The set is connected direct to a step-up transformer having a reactance of 10 per cent. Estimate the values of the short-circuit kVA. with faults on alternator connections and transformer line connections respectively. What would be the approximate value of the electro-magnetic forces with bus-bars spaced at 12 in. centres on the lower voltage side ?

$$\text{kVA. rating} = \frac{50 \times 1{,}000}{0 \cdot 8}$$

$$= 62{,}500$$

Here the reactance of the alternator would only be effective. It should be borne in mind, however, that all possible feeds from the system under consideration should be allowed for.

$$\text{Short-circuit kVA. available} = \frac{62{,}500 \times 100}{15}$$

$$= 416{,}000$$

Corresponding short-circuit current

$$I_{RMS} = \frac{416{,}000 \times 1{,}000}{\sqrt{3} \times 13{,}500}$$

$$= 17{,}800 \text{ amps.}$$

Adopting the notation specified in B.S.S. No. 159/1932.

(*a*) Allowing for resonance

$$F = \frac{5 \times 4 \cdot 5 \times L \times I_s^2}{\quad} \times 10^{-8}$$

Where 5 = resonance factor.

I_s = initial R.M.S. value of the symmetrical component of the S.C. current.

L = length of conductor under consideration in inches.

r = spacing of centres of conductors in inches.

F = maximum instantaneous force in lb.

(*b*) Neglecting resonance

$$F = \frac{4 \cdot 5 \times L \times I_a^2}{r} \times 10^{-8}$$

Where I_a is the initial R.M.S. value of the asymmetrical current.

Since $I_a = \sqrt{3}\, I_s$

$$F = \frac{4 \cdot 5 \times L \times 3 \times I_s^2}{r} \times 10^{-8}$$

(*a*) Allowing for resonance.

$$F = \frac{5 \times 4 \cdot 5 \times 12 \times 17{,}800^2}{12} \times 10^{-8}$$

$$= 71 \cdot 5 \text{ lb. per ft.}$$

(*b*) Neglecting resonance.

$$F = \frac{4 \cdot 5 \times 12 \times 3 \times 17{,}800^2}{12} \times 10^{-8}$$

$$= 42 \cdot 5 \text{ lb. per foot.}$$

(2) Fault on transformer line connections.

Here the reactance of both alternator and transformer would be effective.

$$\text{Short-circuit kVA. available} = \frac{62{,}500 \times 100}{(10 + 15)}$$

$$= 250{,}000$$

Corresponding short-circuit current

$$I_{RMS} = \frac{250{,}000 \times 1{,}000}{\sqrt{3} \times 13{,}500}$$

$$= 10{,}650 \text{ amps.}$$

The electro-magnetic forces can be estimated in a similar manner to that under (1). To estimate the forces on the higher voltage connections and cables it will be necessary to substitute the higher voltage in place of 13·5 kV. to find the current flowing.

Generally these connections will be made by cables and where

single-core cables are used suitable supports should be provided to prevent spreading under short-circuit conditions. On examination of the diagram of main connections for a large inter-connected system it will be appreciated that great care is necessary so that every possible fault condition likely to be met with in practice is provided for. It is necessary to know the initial R.M.S. symmetrical short-circuit current which would be fed back through the connections in the event of a fault in the alternator or its connections, together with the clearing time. These figures enable the electromagnetic forces to be estimated and the strength of the copper connections and supports to be checked. The connections should be designed to have at least the same short-circuit capacity as the controlling switchgear. In one case the switchgear had a rating of 1,000 MVA and circuit breaker clearance time at this symmetrical short-circuit value of about 0·113 second. To this must be added the time taken for the Merz-Price relay to operate plus the time of operation of the inter-tripping auxiliary relay which may be about 0·04 to 0·05 second.

Considering the case of a large lower-voltage (6·6 to 14 kV.) alternator connected to a step-up transformer which forms part of an inter-connected system the possible fault kVA. on the alternator and unit transformer connections is 2½ times that due to the alternator alone. The actual figure will, of course, depend on the system employed.

Where cable connections are made to unit transformers special attention should be given to the design of the sealing ends or trifurcating box if three-core cables are used. In any case the cables should be specially braced and designed to withstand the worst possible fault currents.

Bus-bar joints are usually left untinned. Allowable current densities in bus-bars and connections are :—

Contact surfaces (bolted) . .	125	amps.	per square inch.
Contact surfaces (tinned and bolted)	200	,,	,,
Bus-bars (indoor and enclosed) .	750	,,	,,
Bus-bars (outdoor) . . .	1,200	,,	,,
Isolating switches, etc. . .	50–100	,,	,,

The alternator terminals and connections in the air circuit may be highly rated. An alternator having a full load current of 2,850 amps., the surface contact area 16 sq. in., and sectional area 1·125 sq. in., the corresponding current densities are :—

Contact surface . $\frac{2{,}850}{16} =$ 180 amps. per square inch.

Sectional . . $\frac{2{,}850}{1{\cdot}125} = 2{,}500$ „

A 30 MW, 33 kV. alternator (650 amp.) had a similar contact surface density but a much less sectional density.

Care is necessary when installing and connecting bare copper work and sealing ends to ensure that the contact surfaces are properly made. Cases are on record where portions of the contact surfaces have been covered with insulation, resulting in overheating. In one case the connection to a sealing end overheated to such an extent that the connecting copper strap burnt through causing flash-over to the stator end winding with disastrous results. This was a 30 MW, 11 kV. set which had been in commercial operation for over seven years.

The permissible temperature rises relating to bus-bar arrangements are dealt with in B.S.S. 159/1932, some of which are :—

Temperature rise at standard-rated current :—

(1) For unprotected bare conductors in direct contact with air and rated at 2,000 amps. and below the temperature rise shall not exceed 40° C. (72° F.).

(2) As above, but over 2,000 amps. the temperature rise shall not exceed 50° C. (90° F.).

(3) For all other types of bus-bars and connections the temperature rise shall not exceed 50° C. (90° F.).

The expansion may be estimated from the usual formulæ :—

$$L_2 = L_1 (1 + \alpha T)$$

Where L_1 is the original length of the bus-bar in inches.
L_2 is the new length of the bus-bar in inches.
T is the temperature rise °C.
α is the coefficient of expansion (0·0000166 per °C. for copper).

Rotor. The cylindrical or non-salient pole type of rotor is adopted for turbo-alternators. There are numerous forms of construction, some of which are :—

(*a*) Core built up of a number of steel plates shrunk on to the shaft and slotted after assembly to receive the winding.

(*b*) A three-piece rotor made up of two ends and a centre portion.

(*c*) A single forging.

Although an alternator rotor forging is not subjected to high working temperatures it is of utmost importance that great care should be taken during the process of manufacture. The output of an alternator at a given speed is chiefly limited by the dimensions of its rotor. The diameter is limited by the allowable mechanical stresses whilst the rotor length is determined by the permissible deflection. Rotors have burst, causing extensive damage. Where the shaft has a core made up of a number of steel plates it is fluted and the plates are separated from each other to enable cooling air to circulate. As a certain portion of the magnetic flux between adjacent poles passes through the shaft the fluting on the shaft of a two-pole alternator is arranged differently from that on the shaft of a four-pole alternator. The radial air gap is about 1 in. on a 30 MW 3,000 r.p.m. alternator. The circumference of the rotor body is provided with radial slots machined parallel to the rotor axis to carry the exciting windings. The windings are of copper strip formed on edge and insulated throughout with mica. All joints between coils are either silver soldered or brazed. The slots are lined with cells of moulded micanite and the end-turns are also insulated from each other with mica. Relative movement of the end turns is eliminated by treated asbestos inserted between the coils. By packing the end windings solidly, movement due to the phenomena of coil contraction is prevented. Once the windings have pulled in sufficiently to take up manufacturing clearances between the coils and packings no further movement can take place. It would appear that the condition most favourable to rotor coil distortion is that of frequent running up and down. As a further precaution two methods of preheating the rotor windings to their working temperature before running up to speed are possible :—

(1) Preheating the windings immediately before starting up by passing D.C. It is necessary to control heating otherwise damage to the windings is possible. (Time to heat windings to a mean temperature of 80° C. would be about 2 hours.)

(2) Maintaining the windings at a temperature of 70° to 80° C. while stationary.

The disadvantages of such methods are obvious and in practice are not always justified. Rotor preheating is undoubtedly prolonging the life of older machines but should not be necessary on new alternators to prevent distortion and turn separation. To prevent all risk of arcing between the end-bells and the rotor body

in the event of short circuits a damper winding made from thick sheet copper may be inserted at each end of the rotor. With damping windings a secondary circuit is provided by a solid rotor and wedges and the damping strips under the wedges so that even with the field winding inadvertently open circuited the alternator will still continue to supply power (not wattless kVA) provided the magnetising current now required to excite the alternator can be obtained from the bus-bars. The machine will operate as an induction alternator at a speed in excess of synchronism by an amount depending on the characteristics of the damping winding, probably $\frac{1}{2}$–1 per cent. overspeed. It is desirable that the excitation should be restored as soon as possible since the effective current induced in the rotor damping circuit with the machine on high loads may approach several thousand amps. and the windings are not designed for continuous operation under such conditions. Excessive heating may take place especially at the ends of the rotor where the joints between the body and end cap, and also between the damping strips and the end rings, tend to result in high resistance contacts. (See also Chapter XVIII—Field Suppression).

Movement of the end-turns under the influence of centrifugal force is prevented by enclosing them in massive end-bells or rings made of non-magnetic steel. The design and construction of the end-bells demands special care or trouble may result due to rotation caused by accidental short-circuiting and bursting caused by faulty materials. In early designs manganese bronze was used but after prolonged periods of service it was found under time stress conditions to be unsuitable owing to the development of cracks. The use of non-magnetic material reduces the leakage flux and therefore the eddy current losses at the ends. The inner surfaces of the end-bells are lined with insulating material. The windings are retained in position in the rotor core by means of dove-tail wedges, continuous from one end of the core to the other.

The wedges may be made from steel, bronze or brass and in some designs they are made in two parts. In each case the portion which is nearest to the pole face is of steel and the other is bronze. The bronze portion forms an efficient squirrel-cage damping winding and the steel portion has the effect of reducing the magnetic gap across the winding slots by one half, thus minimising flux tufting and local heating on the surfaces of both stator and rotor. Electrical rotors are tested at a 25 per cent. overspeed for one minute and given a routine test of 15 per cent. overspeed for five minutes, the

balance before and after the test being noted. One method of obtaining the desired speed is to connect the rotor through a gear-box to a D.C. motor which may be operated by Ward-Leonard control.

The rotor winding is connected to two slip rings which may be fitted one at each end or both at the exciter end of the rotor shaft. The rings are of case-hardened steel, nickel steel or tool steel. The

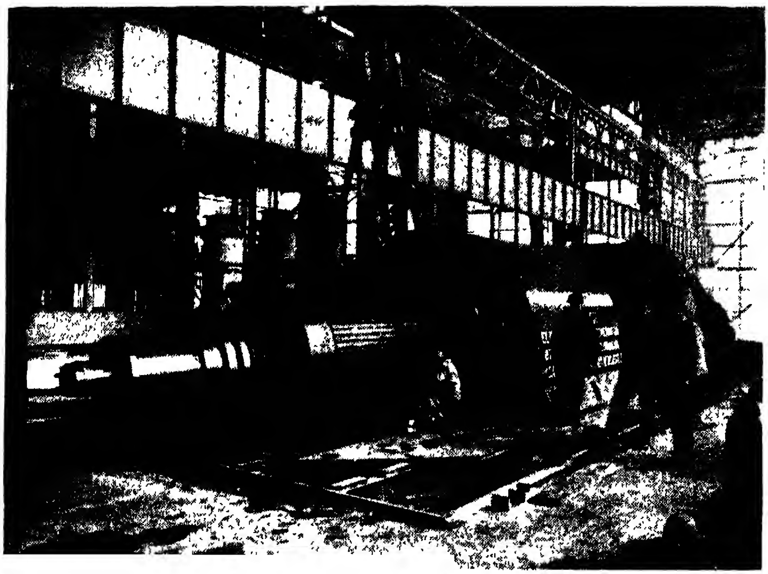


FIG. 395. Threading Rotor for 50 MW Turbo-alternator. (C. A. Parsons & Co. Ltd.)

brush gear is supported from the end shields and totally enclosed. As the peripheral speed of the slip rings is fairly high the brushes should be made of special grade of carbon or graphite. The brushes can be adjusted and replaced whilst the set is running. Instead of the usual plain ring some designs incorporate spiral grooves and others straight grooves to prevent sparking and flats by relieving air pressure under brushes. It also prevents hammering and bouncing of the brushes, dust packing and ensures better contact.

To facilitate erection of the rotor and subsequent removal at any time for inspection purposes special lifting gear is provided. A shield plate is inserted in the stator to prevent damage to the core during the insertion or withdrawal of the rotor. Fig. 395 shows a rotor being threaded into a stator.

Although electrical rotors are in general reliable there are occasional troubles and some data relating to 20 MW, and 30 MW, 6·6 kV. sets are given. The insulation resistance was 1·3 megohms when stationary. On running up the set to speed and testing the voltage to earth from each slip ring it was found that an earth fault had developed which disappeared when the speed was reduced to 900 r.p.m. (3,000 r.p.m. set).

Voltage across slip rings . . .	150 volts.
,, to earth at turbine end . .	40 ,,
,, ,, ,, exciter end . .	110 ,,

Readings indicated that the earth was at the top of No. 3 coil of No. 1 pole and it was possible to effect a repair on site.

On a 30 MW 6·6 kV. set the following readings were obtained with the set running on load with its own exciter :—

Voltage across slip rings . . .	166 volts.
,, to earth at turbine end . .	157 ,,
,, ,, ,, exciter ,, . .	9 ,,
Rotor current	185 amps.

Tests indicate that the earth is near the exciter end slip ring. These figures were not obtained with brass wire brushes and therefore include the brush drop which may modify the apparent position of the rotor earth fault. Such faults have been known to obtain for quite a few months without giving further trouble, but the danger of a second earth occurring should not be overlooked. Should the second earth be such that coils are cut out only in one pole, excessive vibration may occur owing to the unbalanced magnetic pull. If the second earth occurs near the turbine end slip ring, the majority of the windings will be cut out and the exciter will be subjected to a short-circuit or partial short-circuit and may be seriously damaged. If the earth faults are close together in the length of the windings with a comparatively low voltage difference between them, or if one earth fault has a small resistance, a short-circuit current of some 200 amps. may flow, which may result in serious burning of the rotor teeth or body in the vicinity of one or both of the earth faults. Cases are on record where, if the double earth fault had been maintained much longer, a new rotor forging would have been necessary.

The rotor may be tested at 400 volts A.C. both stationary and running up to speed also balanced and overspeeded to about 20 per cent.

Rotor coil contraction has been a source of trouble and effective

dissipation of the heat appears to be the only solution. No copper shortening shall take place under operating conditions.

Some data relating to modern turbo-alternators are given in Table 51.

TABLE 51. *Alternator Data*

	Type		11 kV. 50 MW 1,500 r.p.m.	11 kV. 30 MW 3,000 r.p.m.	33 kV. 30 MW 3,000 r.p.m.		
Stator	Alternator weight, tons		136	80	97	120	104
Stator	Conductor area square inches		1·68	1·2	0·52	0·425	0 35
Stator	Current density amps. per square inch		1,880	1,640	1,300	1,500	1,880
Stator	Conductors per slot		1	2	3 triple concentric	6	4
Stator	Insulation		Micanite	Micanite	Micanite	Mica	Micanite
Stator	Thickness of Insulation	To earth . in	0·16	0 17	0 57	0 4/0 3	Graded 0·375/0·15
Stator	Thickness of Insulation	Between turns in.	Each turn in sep slot	0 34	0 16	0·3/0·25	Sep. wrap.
Stator	Stator weight . . . tons		82	60	72	85	83
Rotor	Rotor weight . . . tons		55	20	17–26		
Rotor	Peripheral speed . ft. per sec.		350	484	437–498		
Rotor	Critical speed . r.p m		1,950	1,455	1,285–2,300		
Rotor	Insulation		Moulded Micanite	Moulded Micanite	Mica or Micanite		
Rotor	Thickness of Insulation	To earth . in.	0·05	0·04	0 04		
Rotor	Thickness of Insulation	Between turns in.	0·014	0 014	0·014		
Rotor	End-bells insulation		Micanite	Mica or Asbestos	Micanite		
Rotor	Thickness of insulation . in.		0·125	0·125	0 093/0·125		
Rotor	Material		Non-magnetic steel	N.M. steel	N.M. steel		
Rotor	Max. stress tons per square inch		13·8	18	15		
Rotor	Max. pressure of winding on end-bells . lb. per square inch		2,660	5,000	4,300		
Slip Rings	Material		Tool steel	Case-hardened steel	Forged steel		
Slip Rings	Brushes per ring		16	8	10		
Slip Rings	Material		Carbon	Graphite	Graphite		
Slip Rings	Area of brushes per ring square inches		12·5	6 25	13		
Slip Rings	Current density amps. per square inch		47	50	25		

Bearing Pedestals. As mentioned in Chapter IX (Oil Systems), the outboard bearing of the alternator and exciter pedestal are insulated from the bedplate. Cases are on record where static electricity has proved a nuisance on these parts of turbo-alternators and rubber mats have been provided along each side. Rubber mats are chiefly of value during maintenance of exciters whilst in service. The alternator excitation circuit is normally insulated from earth and, provided the insulation is high, no shorts should be experienced when touching any live parts. Should the insulation deteriorate, or if a static charge is built up on the excitation circuit, a slight shock may be experienced. Phenomena resulting from static electricity due either to the friction in the journals or a leakage from the excitation circuit has been experienced. The potential of the outboard bearing and exciter pedestal above earth can only build up if the insulation resistance of the oil films of all the bearing surfaces, including oil pump and governor drives, is high, thus preventing the leakage of any static charge. Any baffles must also be clear of the shaft. If the resistance of the oil films at the steam end of the set is fairly low the voltages induced in the rotor shaft, both A.C. and D.C., will result in a difference of potential between the outboard bearing and exciter pedestal and earth. This may vary between 1 and 8 volts but has no injurious effects upon the plant since the pedestal insulation prevents circulation of current through the bearings. To determine the condition of this insulation connect a 4-volt lamp between the insulated pedestals and earth. If the lamp lights the insulation can generally be considered satisfactory although a dim glow does not necessarily imply faulty insulation. The voltage induced in the rotor shaft may be due to unbalanced flux in the rotor returning to the stator core *viâ* the bearings; to A.C. fluxes which are cut by the rotor; or to static charges which may build up on the shaft. The first may be due to unequal air gaps, unsymmetrical arrangement or construction of the stator end windings, the axial magnetisation of the shaft, or a short circuit of part of the rotor windings. The second may also be due to unequal air gaps, inequalities or dissymmetry in the stator magnetic circuit, or to unbalanced loads. Such conditions are common to all types of alternators irrespective of voltage.

Exciters. The exciter or exciters as the case may be are, next to the alternators, the most important items of electrical plant. The direct-current generator used for supplying the excitation current has to work under unfavourable conditions. The magnitude

of the main excitation current is adjusted by alteration of the exciter voltage and in practice this has to be varied over wide limits. The inherent instability of a shunt-exciter is shown in Fig. 396 which gives the magnetisation curve, OBE, of the exciter. The line OD represents, by its slope, the resistance of the exciter field circuit, including regulating resistance. When the machine is running and the field circuit is closed it will excite itself to a voltage corresponding to point D. The exciter voltage, and therefore the alternator field current, will be quite stable under these conditions. If load be taken off the alternator a reduction in field current is necessary which is brought about by adding resistance to the exciter field circuit. Suppose the new field circuit resistance is represented by the slope of the line OC it will be observed that this resistance line runs almost parallel with OBE between A and B. The voltage may take up any value between these points and may fluctuate between the two, being quite unstable. Corresponding variations take place in the alternator field current which would result in unsatisfactory operation. Two exciters are now provided, the main exciter and a service exciter. The latter is a shunt wound machine and supplies the field current for the main exciter which in turn provides the field current for the alternator. The idea underlying this method is that under all conditions the excitation system remains perfectly stable. The two exciters are coupled to the alternator. The possibility and advisability of making the exciter remote from the turbo-alternator has been given considerable thought, there are obvious advantages, however, that justify the exciter being directly coupled to the main set, namely :—

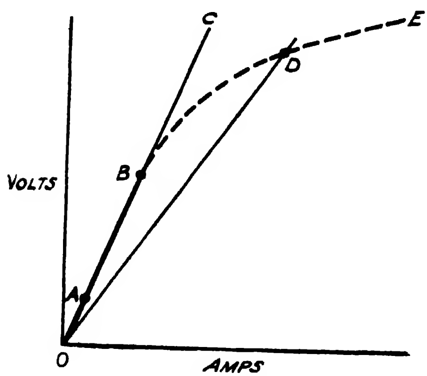


FIG. 396. Exciter Magnetisation Curve.

(1) The machine as a unit is complete in itself and independent of outside sources for its operation.

(2) The voltage of the system can be maintained independent of any auxiliary source of supply and is not affected by faults thereon.

(3) It will probably command greater respect since it forms part of an important section of plant.

The disadvantages of direct-coupled exciters are :—

(1) With the high speeds in general use (1,500 and 3,000 r.p.m.) difficulties such as balancing, coupling up, lining up and shaft problems are introduced.

(2) Armature fitting, commutator stresses, brush chatter, and ventilation all require special attention.

(3) Exciter troubles may necessitate shutting down the main set.

In practice the commutator appears to require most attention and it is essential that its design and manufacture be given special consideration. The seasoning of commutators is important and manufacturers have different workshop processes. The temperature of the commutator is raised to between 100° and 130° C. and then while hot it is run at a speed of about or just above normal so that all bars that can move are driven out by centrifugal force either on account of their places or of pockets of shellac in the mica vee rings. The bolts are then tightened and the commutator surface ground. The grinding and burnishing of a commutator calls for due care if a satisfactory job is to be ensured. Some makers have discontinued the practice of burnishing. The process was carried out by means of a hardened mild steel wheel of similar dimensions to the abrasive stone used for grinding. It was contended that this process hardened the commutator segments and avoided repeated grinding, consequently increasing the useful life of the commutator. The best results appeared to be obtained when burnishing took place with the armature running at about half normal speed. After a commutator has been subjected to grinding it is advisable to apply the electrical load in small increments until the normal skin or surface is obtained. It appears that during the process of grinding the copper is subjected to frictional heat and this affects its nature. In other words, a process of stress relieving must follow grinding before applying anything near full load to the commutator.

Pronounced sparking, chattering and vibration have followed grinding when the machine has been loaded too rapidly.

Two commutators of $5\frac{1}{2}$ in. and $7\frac{5}{8}$ in. diameters were ground on site, the machines being run at the normal speed of 3,000 r.p.m.

Diameter of grinding wheel	12 in.
Types of wheels . .	Rough carborundum used first and finished with a smooth fine stone.
Speed of grinding wheel .	1,600 r.p.m.

In some cases the armatures have been removed from the

machines and turned in a lathe (commutator speed of 300 ft./min.) with good results. Turning is more efficient than grinding for removing much metal, but grinding gives a much better finish when only a little metal has to be removed. The final grinding of a commutator must be done at normal speed as a certain amount of whip occurs, therefore the soundness may not be perfect if carried out below normal speed. For turning, the speed should not be high ; a high-speed causes a rough cut. A commutator speed of 1,000 ft. per minute and a grinding wheel speed of 50 ft. per minute in the reverse direction of rotation have been suggested.

During the grinding process the exciter field system is completely removed and the armature taped to prevent the ingress of dust, etc. Faulty commutator riser joints are sometimes encountered and these in turn may affect the binding wires.

To overcome commutation difficulties some makers fit two brushes per box instead of the more usual one, the brushes being half the thickness. Better contact is ensured under the high speeds.

In the latest stations, however, where 75 MW 1,500 r.p.m. sets and 60 MW, 3,000 r.p.m. sets are installed, direct-driven exciter units have been used and are giving satisfactory service. Certain manufacturers have evolved designs in which the exciters are geared down from 3,000 r.p.m. to 1,500 r.p.m. One 125 MW (American) machine has the main and pilot exciters driven through reduction gearing from alternator at about 990 r.p.m. A number of stations have separate motor-driven standby exciters and in addition arrangements are made whereby a supply can be taken from batteries. A motor generator standby exciter set is very useful in case of exciter failure, and in some stations arrangements are made so that it may be connected to any exciter. Two points worthy of attention in regard to standby exciter sets are : (1) the current rating should be such as to deal with any alternator output, (2) the no-load excitation of all alternators should be catered for so as to permit of synchronising, and this necessitates the exciter rheostat being capable of bringing the voltage down to the desired minimum.

Taking two 30 MW, 3.000 r.p.m., 33 kV. sets of different make, the synchronising field figures (alternator no-load excitation) were :—

Set "A"	85 volts,	113 amps.
,, "B"	68 ,,	90 ,,

Fig. 397 shows a diagram of this equipment.

In one station a separate exciter is driven by a 300 B.H.P. 3.300 volt slip ring induction motor, and this set is also used for battery charging. Another station has a motor-generator set consisting of shunt wound generator, 90 kW., 600/320 amps., 150/250 volts; motor, 140 B.H.P., 400 volt, 965 r.p.m., 3-phase; largest set-30 MW.

The main and standby exciters can be connected to their own field suppression pillars and terminal boards and by changing over

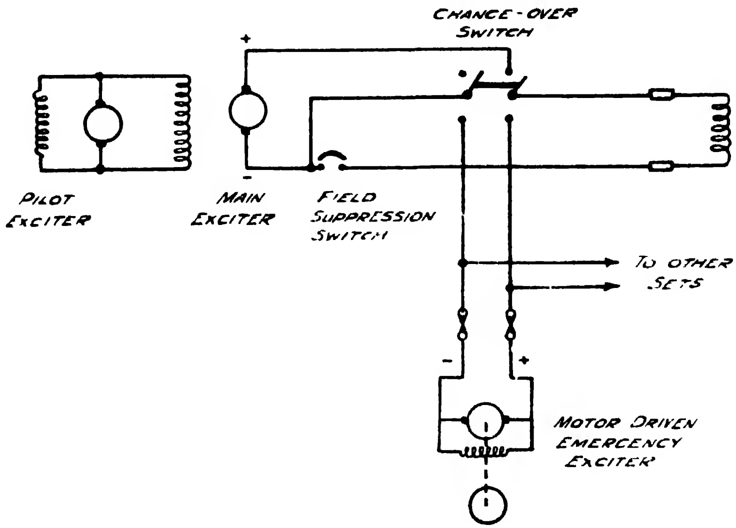


FIG. 397. Emergency Excitation Circuit.

certain links the standby supply can be brought into service without interfering with the normal alternator protection.

A steam driven exciter is independent of system troubles and is equal in reliability as the main exciter on the alternator shaft, and considering both cost and reliability a steam driven non-condensing set has much in its favour.

Characteristic excitation curves for a typical turbo-alternator are shown in Fig. 398 and Fig. 399 gives typical open-circuit characteristics. With the large reactance and wide inherent regulation of modern alternators the voltage variation of the exciting circuit under varying conditions of load is fairly wide. In large alternators the ratio between the slip-ring voltage at no-load and that corresponding to maximum output may approach one to four.

In such conditions the excitation of several alternators from common bus-bars is inadvisable because of the large rotor field rheostats which would be required and the necessary accommodation. A further objection to the use of rheostats in the rotor field is that any surge on the line is transferred inductively into the rotor windings

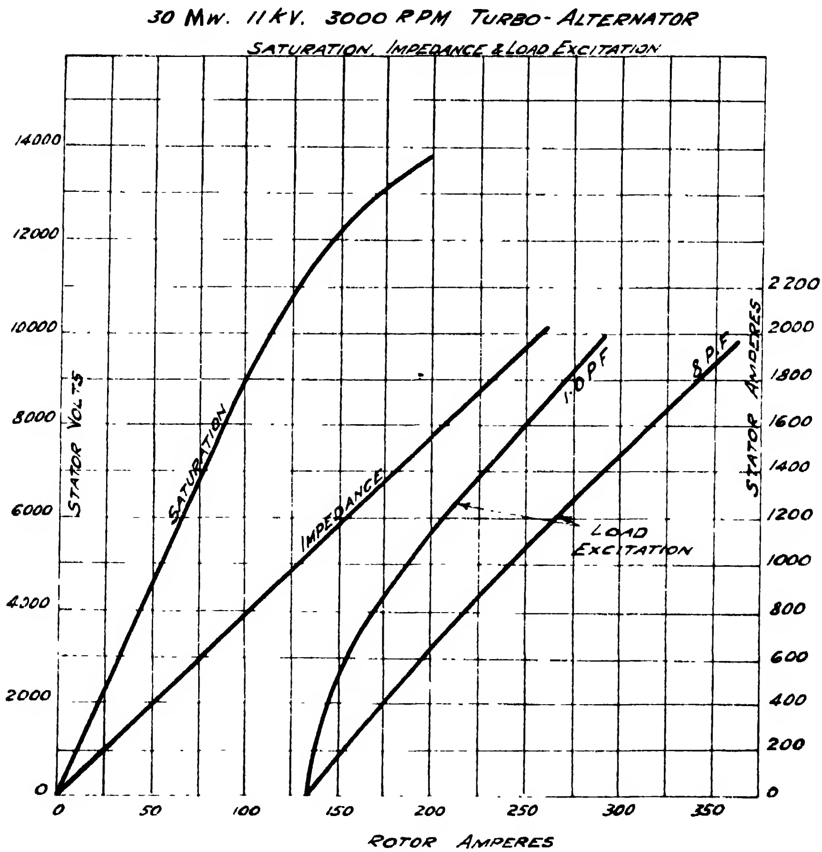


FIG. 398. Characteristic Excitation Curves.

and may cause an abnormal increase in voltage if the external circuit has any appreciable resistance. Exciter breakdown has in some cases been attributed to this form of fault. A separate exciter direct-coupled to the alternator and controlled by its own field rheostat therefore affords the best method of excitation apart from the independent exciter.

Unsatisfactory operation may be experienced on large systems when there is a surge or other disturbance and the exciter either

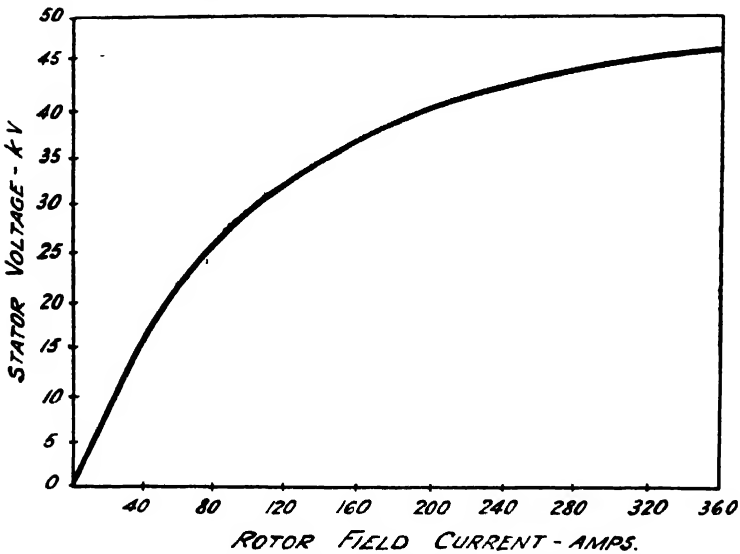


FIG 399. Open-circuit characteristic for 33kV, 30 MW Turbo-alternator.

loses its voltage or changes its polarity. This effect is due to sympathetic impulses of current passing through the excitation system from the rotor with every change of current in the stator windings, and is most pronounced at low loads when a low exciter voltage is

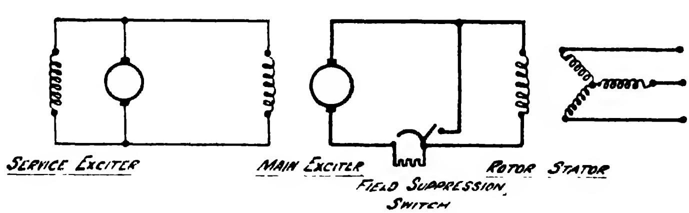


FIG. 400. Diagram of Exciter Circuit.

required and the exciter magnet is unsaturated. This instability of exciter voltage arises in a shunt machine from the fact that the field coils depend for their current upon whatever voltage is available at any instant on the commutator. To eliminate this instability the inclusion of a stabilised or service exciter coupled direct to, and supplying the main exciter is favoured. This small auxiliary

exciter has a saturated magnetic circuit and generates at a constant voltage. In cases where alternators are required to supply abnormal overloads or to be capable of line charging the very large excitation range necessitates the use of a separately excited exciter. The pilot exciter supplies a constant current to a small negative shunt winding in the main exciter and also a current of magnitude controlled by the shunt regulator to the positive main-field winding. Typical diagrams are shown in Figs. 400 and 401.

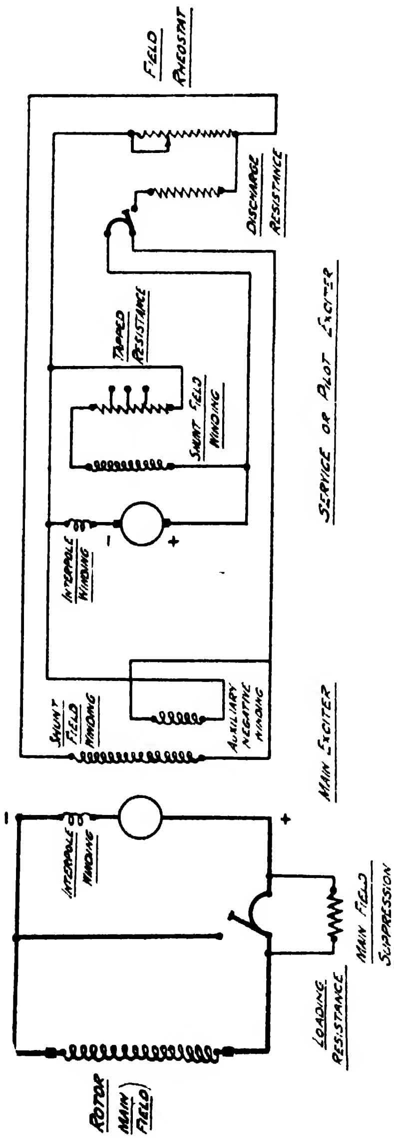


FIG. 401. Excitation Circuit for Large Turbo-alternator.

In this way perfect stability is obtained as the main exciter does not depend for its excitation upon its own varying armature voltage.

This arrangement enables the voltage of the main exciter to be reduced to a very low figure and avoids the sluggish operation of the automatic voltage regulator. The auxiliary negative shunt winding brings about a reduction in resistance required for the main exciter rheostat. It is possible to obtain the same result by separately exciting the main exciter from a battery or other external supply, but the question of reliability must be kept in mind.

The inclusion of a pilot exciter has a further advantage in that response to any new load condition on the alternator is much quicker than when the main exciter is self-excited. In some cases the pilot exciter gives

supply to the governor motor and alarm circuits. This method of supply is not recommended as faults on these auxiliary circuits may cause a serious disturbance on the alternator and might possibly result in the set having to be shut down.

Data for typical exciters are given :—

125 MW, 16·5 kV., 3,600 r.p.m. alternator.
Main exciter, 340 kW., 375 V.
Pilot exciter, 2.5 kW, 250 V. (A.C. permanent magnet type)
(Exciters are driven through reduction gear).

75 MW, 12·5 kV., 1,500 r.p.m. alternator.
Main exciter, 175 kW., 330 V., 530 A.
Pilot exciter, 10 kW., 250 V., 40 A.

50 MW, 11·4 kV., 1,500 r.p.m. alternator.
Main exciter, 210 kW., 325 V., 650 A.
Pilot exciter, 6·6 kW., 220 V., 30 A.

30 MW, 33 kV., 3,000 r.p.m. alternator.
Main exciter. 100 kW., 300/450 V., 315 A.
Pilot exciter, 1·65 kW., 110 V., 15 A.

3·5 MW, 3 kV., 3,000 r.p.m. alternator (house set).
Main exciter, 25·3 kW., 155 V., 350 A.
Pilot exciter, 3 kW., 125 V., 24 A.

Exciter data are given in Table 52 (p. 160).

The question of alternator stability has received much attention and is closely related with the rate of excitation response. The maximum stable load may be raised by increasing saturation in the magnetic circuit. An alternator operating on a load beyond the load limit may be unstable unless the voltage can be maintained. With a lagging load an increase in the load current beyond the load limit causes the voltage to fall and, although the load may remain constant greater excitation may be required. An even greater excitation is necessary to restore the voltage to normal, and in order to prevent the voltage falling it is essential to increase excitation immediately at a higher rate than the increasing demand. The excitation response required to restore the voltage is determined by the rate at which it falls and this in turn depends on the time constant of the alternator under the particular conditions of operation. The rate of response of excitation for these conditions is of the order of 150 volts per second for a 250 volt exciter. With a

TABLE 52. *Exciter Data*

kVA. rating	25,000	31,250	37,500	37,500	37,500	62,500
Voltage	6,600	11,400	11,400	11,400	33,000	11,400
Main excitation volts. Full load	255	256	312	218	300	295
Main excitation volts. Open circuit	60	65	74	61	65	98
Main exciter ceiling volts	360	350	350	312	450	460
Pilot exciter volts. Full load	—	—	—	250	108	220
Pilot exciter volts. Open circuit	—	—	—	274	110	220
Pilot exciter ceiling volts	—	—	—	274	110	220
Approximate per cent. drop in exciter voltage for 2 per cent. drop in speed at F.L.	8	4·5	4·5	—	5	—
Ditto for 4 per cent. drop	16	10	10	—	10	—

leading load an increase in the load angle beyond the load limit is cumulative and if the excitation can be increased sufficiently rapidly before the angle becomes appreciably greater than 90°, stability should be maintained. It is estimated that for a typical turbo-alternator an excitation response of 300 volts per second for a normal excitation of 250 volts should be ample if immediately required.

Voltage Regulators. When an alternator is supplying current its terminal voltage drops by an amount which depends upon the magnitude and phase of the current, a leading current causing an increase in voltage generated and a lagging current resulting in a drop in voltage. If the load changes slowly or can be fairly accurately ascertained beforehand any adjustments can be made by hand regulation. To make the alternator self-regulating an automatic voltage regulator may be used. In addition to keeping the correct voltage within close limits a regulator assists in maintaining the

stability of the alternator under abnormal conditions of load. A diagram of connections of a typical automatic voltage regulator with field forcing equipment is shown in Fig. 402. The operation

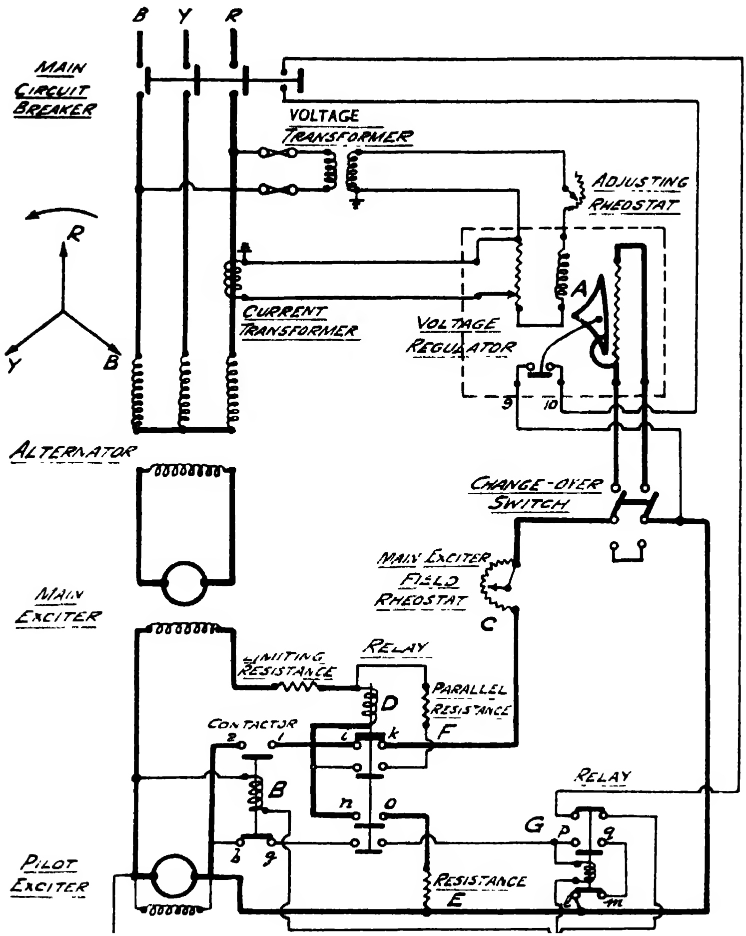


FIG. 402. Automatic Voltage Regulator with Field Forcing Equipment. (Brown, Boveri & Co. Ltd.)

of this regulator will be followed from the general notes. In the event of a heavy fall in voltage such as would be caused by a fault, the pointer A of the regulator swings over to the extreme right-hand position and closes the auxiliary contacts 9 and 10. This operation

energises the coil of the contactor B, which closes the contacts 1 and 2, thus shorting the resistance which remains in the field rheostat C. The exciter field current rises and in doing so exceeds the pick-up value of the relay D. Its armature rises, thus disconnecting the automatic voltage regulator resistance by means of the contacts i and k and at the same time connecting across the contacts

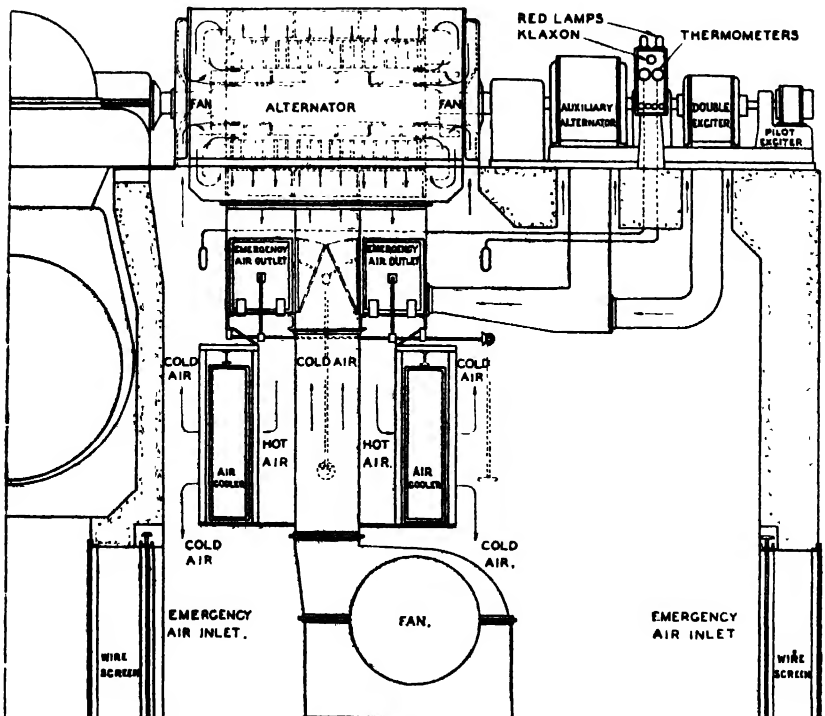


FIG. 403. Simplified Diagram of Closed Circuit Ventilation System for Large Turbo-alternator with Supplementary External Fans. (Metropolitan Vickers Electrical Co. Ltd.)

of the contactor a diverter resistance E *viâ* contacts n and o. The resistance F is connected across the relay coil by the same action in order to shunt some of the current from this coil and thus adjust its fall-back value. The object of the operations which are carried out by the relay D is to prevent excessive current flowing through the automatic regulator resistance when the contactor opens. Assuming now that the bus-bar voltage has risen to its normal value the regulator pointer A will move over towards the

left thus opening the auxiliary contact and de-energising the contactor which will open. The exciter field current is now limited by the diverter resistance E and when it falls below the fall-back value of the relay D the armature of the latter falls, thus re-closing the automatic voltage regulator circuit and restoring the regulation to normal. In the event of a sustained overload the above process will be repeated until such time as the load comes within the normal rating of the machine. The function of the relay G is to prevent continuous hunting of the equipment between the normal and field forcing conditions. It is provided with a time lag between the armature and the contacts l and m and it operates immediately the contactor falls back, its coil being energised from the pilot exciter *viâ* the contacts b and g of the contactor and the contacts of the relay D. When the armature lifts it closes its hold-on contacts p and q and opens the circuit to the contactor coil. The contactor is thus prevented from re-closing until the contacts l and m have opened the coil hold-on contacts. The change-over switch for cutting out the regulator is of the " make " before " break " type. Reference should be made to the manufacturer's instructions for connections of the current and voltage transformers. Care should be taken to ensure that the voltage transformer is in circuit for the regulator voltage control.

The necessity for field forcing equipment depends to some extent on the design and operating practice of the electrical distribution system. The main advantage is to maintain bus-bar fault voltage at a higher value under fault conditions and so improve the system stability. The disadvantage is that damage to switchgear may be greater due to the higher fault MVA. The question arises as to the maximum value of the voltage under the control of the field forcing equipment. Some makers consider that the rate of response, *i.e.*, the rate of build up of exciter voltage is of more importance than a high maximum voltage on the exciter in maintaining stability. The contactor should increase exciter voltage about 25 per cent. above that corresponding to M.C.R. conditions. The selection of a comparatively low tapping for the contactor has the advantage that the fault MVA and the duty of the switchgear is not increased to any appreciable extent. It may also be necessary to prevent excessive wattless current being carried by the set should it be running in parallel with other sets which are on hand control or have automatic voltage regulators with less margin. A further advantage is that it will limit the sustained unbalanced fault current

in the event of a fault between two lines or from line to earth which may lead to serious overheating of the rotor. Electronic alternator voltage control has also been tried but is not in common use. Electronic tube automatic voltage regulators have been developed in several forms, some using only one tube and others several tubes. Such tubes have no time lag, require small power and thus have high sensitivity and speed of response. Field forcing is made possible by the regulators ability to provide rapid voltage across the exciter shunt field coils in excess of the armature voltage.

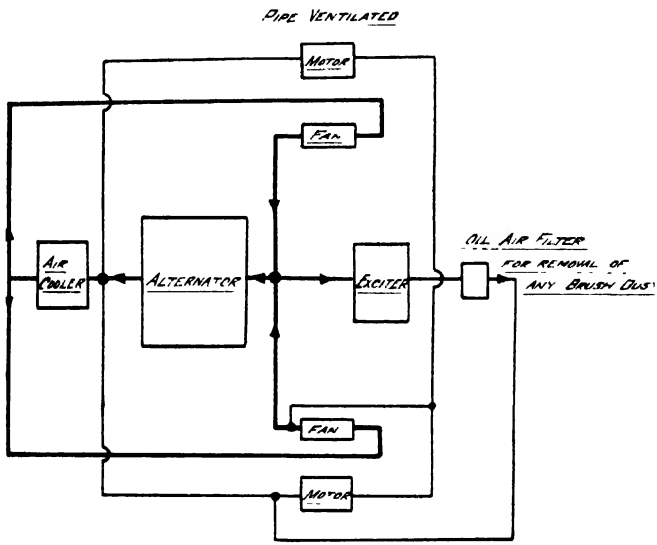


FIG. 405. Diagrammatic Layout of Alternator Ventilating System.

Ventilation. The ventilating system, while being simple should be such that the alternator is cooled uniformly throughout its entire length. Typical ventilation systems are illustrated in Figs. 403 to 405. With the larger sizes and longer lengths of modern alternators this becomes increasingly difficult. To facilitate matters the air passage is sub divided into parallel air circuits arranged axially, offering a low resistance to the passage of air. The older system of ventilation in which the cooling air was discharged to the atmosphere after passing through the alternator has been superseded by the closed circuit system for all large machines. In this system the same air is circulated continuously through the alternator and is cooled by being passed through a cooler. The same air being used continuously prevents the ventilating ducts becoming choked

with dust and the winding insulation being damaged by abrasion of grit. To prevent oil from the bearings being drawn along the main shaft, air under pressure from the delivery side of the fan may be admitted into a sealing chamber surrounding the shaft and be maintained at about 6 in. water gauge above atmosphere. The slight air leakage around the shaft suffices to prevent oil or oil vapour being drawn into the alternator.

The advantages of this system are :—(1) Very little or no dirt can collect in the alternator. (2) Fire-hazard is reduced since the quantity of oxygen in the system is limited. As a further precaution the ducts and chambers can be arranged for flooding with inert gas. (3) Obviates the expense of frequent and messy cleaning of filters. (4) Reduces noise in turbine house. (5) Temperature of turbine house is lower, which is an advantage in hot climates. (6) The ultimate air temperature is dependent only on the temperature of the cooling water. (7) A very compact system is obtained, for in most cases it is possible to install the cooler and fans in the alternator foundation block, the only external plant being the fan motors and the pipe connections to the cooling water supply. The fan bearings are accessible even when the plant is running. In some cases the fan and the motor rotor are mounted on a common shaft which necessitates complete dismantling of the unit in the event of a faulty rotor. Such failures are rare in modern motors but are worthy of consideration where fans of limited output are installed, otherwise the alternator may be put out of service or at least have to be run at reduced output. Means are provided so that in the event of a burst tube, failure of cooling water supply or other emergency, air can be immediately admitted from outside. There is always a certain amount of leakage of air from the closed system no matter how carefully the joints are sealed, and in order to provide for this, make-up air may be arranged to enter *viâ* a filter fitted in the wall of the foundation block. In this way the make-up air is comparatively clean. Some makers prefer to subject the alternator foundation air circuit to a slight air pressure by means of a small blower discharging into one of the stator side boxes and so detect any point, particularly emergency dampers, of leakage before commissioning. All points of possible leakage are well packed and sealed by lead wool or rope and red lead. The factors influencing the stator cooling air temperature are :—(1) Cooling water temperature. (2) Quantity of cooling water. (3) Atmospheric conditions. (4) Electrical load. (5) Fans in service and positions of dampers.

The use of the closed-circuit system of ventilation opens up the possibility of the application of some other gas as the cooling medium in place of air. Hydrogen is generally considered to offer the greatest advantages as an alternative. Some of the advantages of hydrogen for alternator cooling are :—

(1) The density is only about 7 per cent. of that of air, with consequent reduction in windage losses.

(2) The thermal conductivity is about 7 times that of air and is approximately the same as that of most of the insulating materials used on the windings. Its specific heat is 14·5 times that of air. The heat transfer with forced cooling may be as much as 2 to 3 times that with air.

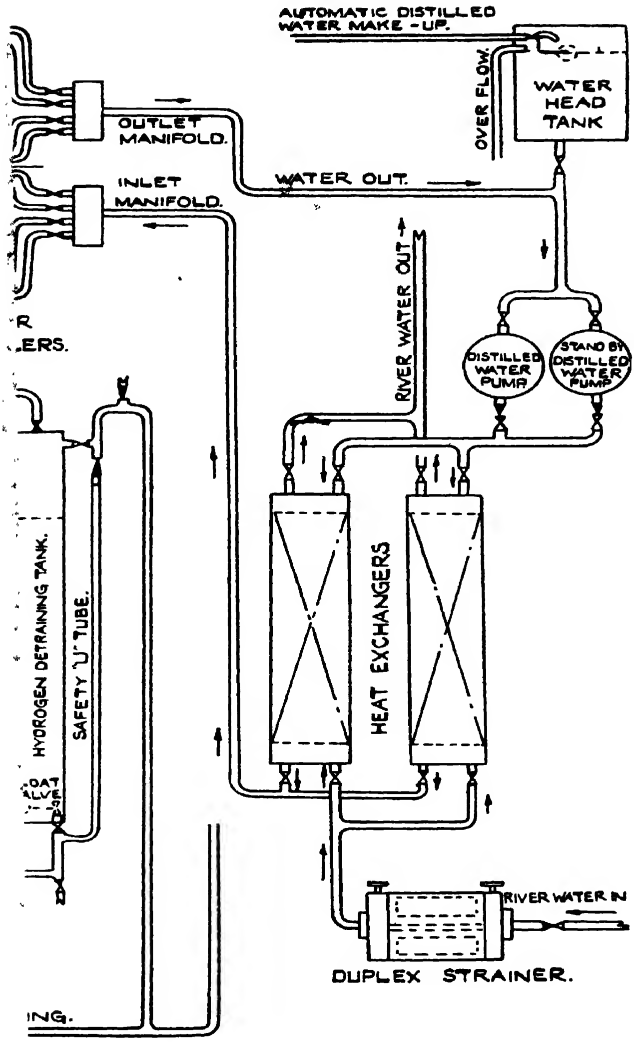
(3) Due to its lower losses and better heat transfer in the cooler, less cooling water will be required.

(4) Hydrogen cooled machines require less space and can be adapted for operation outdoors with very little change to indoor type.

(5) Corona appears in hydrogen at about 60 per cent. of the voltage at which it appears in air of the same pressure, but on the other hand, in hydrogen, corona has no ill effects on fibrous insulation ; nitric acid which is formed by corona discharge in air being absent. The importance of this is apparent in view of the desire to increase the voltage on large alternators.

(6) The fire risk is reduced in the event of electrical breakdown as oxygen is not present to maintain combustion of the insulating material, the only possibility being if any leakage should occur in the machine casing. The casing is made explosion-proof against any pressure which can be developed by explosive mixtures of hydrogen and air. To guard against leakage the hydrogen is usually maintained at a pressure of between 1 to 5 lb. per sq. in. above atmosphere so that leakage is outwards into the air. In some stations the outputs of hydrogen-cooled alternators have been increased some 15 per cent. by increasing the average pressure of the cooling gas in the machine from 0·05 to 15 p.s.i. gauge.

The weight of hydrogen to remove a given quantity of heat is much less than the weight of air required, but the volume is about the same in each case so that the ventilating ducts and air passages are therefore almost the same. A hydrogen purity indicator can be used to give warning should the content fall below a predetermined value. The effective sealing off of the shaft glands at the alternator housing is one of the chief difficulties and oil labyrinths


AUTOMATIC DISTILLED WATER MAKE - UP.
OVER FLOW.
WATER HEAD TANK
OUTLET MANIFOLD.
INLET MANIFOLD.
WATER OUT.
RIVER WATER OUT
DISTILLED WATER PUMP
STAND BY DISTILLED WATER PUMP
HYDROGEN DETRAINING TANK.
SAFETY 'U' TUBE.
HEAT EXCHANGERS
RIVER WATER IN
DUPLEX STRAINER.
ING.

[*Facing p.* 166.

appear to be the most satisfactory. It has been estimated that the losses can be reduced by 40 per cent. and the machine output increased some 25 per cent.

A high degree of hydrogen purity is required to ensure high efficiency and avoid explosions, and this necessitates hydrogen purity, pressure and temperature recorders. Hydrogen cooled alternators (60 MW—3,000 r.p.m.) are now in service in this country and efficiencies of 98·5 per cent. at 0·8 power factor are obtained. The increase in efficiency is about 1 per cent. with a corresponding increase in output of some 20 per cent. Machines of 200 MW output at 3,600 r.p.m. are now considered as practicable with hydrogen at 30 p.s.i. for cooling.

Before admitting hydrogen to the cooling system it is usual to displace the air with CO_2 to avoid an explosive mixture in the stator casing. When removing hydrogen from the system, it is displaced by CO_2 which in turn is removed by compressed air.

Figs. 406 and 406A show typical diagrams of the associated plant.

Air Filters. Filters are seldom adopted although they are still favoured for small sets. The type used is the viscous filter which consists of a number of shallow boxes containing brass ferrules, expanded metal or baffles which are covered with a film of oil. The air is forced to take a tortuous path through the sections and in so doing dirt is collected by the oil film. For the ventilation of the exciter and slip rings of large sets a portion of the cold air from the fans is diverted from the main air circuit. It is returned to the circuit through filters of the viscous type to remove any carbon or metallic dust produced by the brushes, slip rings and commutators before it again circulates through the set. The filters should be periodically inspected and, if necessary, thoroughly cleaned. After cleaning the filters should be dipped in an oil of high viscosity and all surplus oil drained off. The main and pilot exciters are usually constructed in one frame which is enclosed and in some designs the armature and field windings only are ventilated by air drawn from the alternator closed air circuit. The quantity of air is very small and it is sometimes allowed to re-circulate in the cool air space of the alternator. The commutators are not included in the ventilating system but are external and left open to the atmosphere except for a canopy. In this way carbon and metallic dust does not enter the air system and filters are not required. Another advantage claimed for this arrangement

is that the brushgear and commutators are always accessible and clearly visible at all times, which is considered a desirable feature for high-speed commutators. The totally enclosed arrangement with inspection windows has proved very satisfactory in service.

Air Coolers. The air cooler is similar to a motor car radiator but has the reverse operation, its function being to absorb heat from the air instead of to dissipate it. It resembles a surface cooler, inasmuch that water is passed through cooling tubes communicating with water boxes or headers at opposite ends of the cooler. The cooler is generally made up of one or more sections each consisting

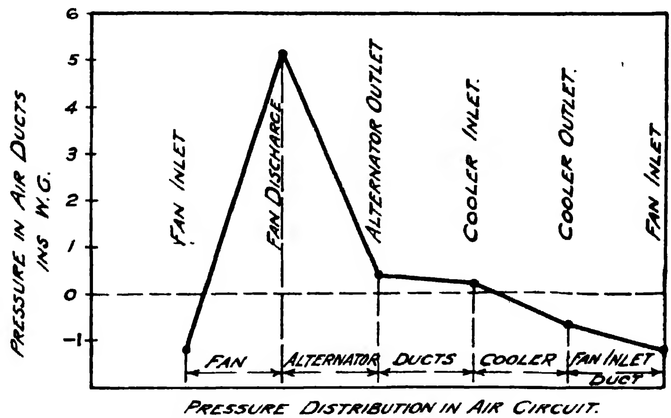
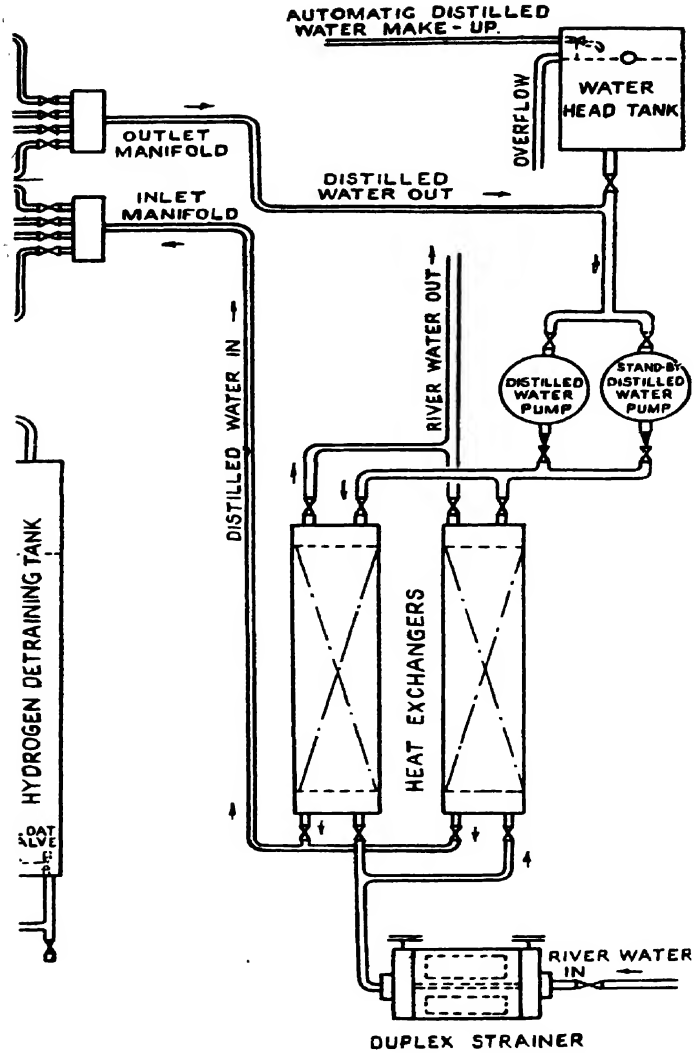


FIG. 407. Water Gauge Losses in Turbo-alternator Closed Air Circuit.

of a nest of tubes. The tubes may be of brass or copper and usually have radial corrugated fins or fine copper wire loops. The limiting factor in the design of air coolers is the comparatively low rate of heat transmission from air to metallic surface which is obtained by arranging a large number of copper fins on the outside of the tubes. The heat transmission rate is a function of the air and water velocities and also of the type of surface in contact with the air. The air and water velocities are largely governed by the permissible pressure drops (Fig. 407) and are generally of the order of 700 to 750 ft. per minute for the air, measured on the frontal area of the tube nest, and 4 to 5 ft. per second for the water flowing through the tubes. At these velocities a tube having flat circular fins would give about 7 or 8 B.Th.U. per sq. ft. per °F. per hour air surface, while a tube having a corrugated helical strip fin would give 10 to 12 and a



AUTOMATIC DISTILLED
WATER MAKE-UP.
WATER
HEAD TANK
OVERFLOW
OUTLET
MANIFOLD
INLET
MANIFOLD
DISTILLED
WATER OUT
RIVER WATER OUT
DISTILLED WATER IN
DISTILLED
WATER
PUMP
STAND-BY
DISTILLED
WATER
PUMP
HYDROGEN DETRAINING TANK
HEAT EXCHANGERS
RIVER WATER
IN
DUPLEX STRAINER

[*Facing p.* 168.

tube with fine copper wire loops sweated on may probably do as much as 18 to 20.

The maximum velocity in the air circuit at certain portions outside the alternator may approach 1,500 and 2,000 ft. per minute, and the minimum velocity, which occurs just after the cooler, may be as low as 500 ft per minute. The tubes may have ferrules at both ends or be expanded at one end. The cooler usually has two sections which are mounted on rollers and guide rails are fitted to the top to facilitate its withdrawal from the foundation block.

The tubes of either section may be cleaned with the cooler in position and one section in service. This is a decided advantage where strainers are not included as the set can then be arranged for continuous service. The cooling water is normally taken from the circulating water system although emergency arrangements may include a supply of water from a service water system or alternatively the town main, the latter being costly if continued for prolonged periods. A relief valve may be fitted to prevent damage in the event of excessive pressure being applied when a discharge valve is closed and the supply being taken from the town main. If dew-point conditions are reached in the air circuit, moisture will be deposited on the cooler surface. Water collected at the base of the cooler can be drained off. The use of condensate has also been tried, in some cases only the first air-cooler section being served from this source. The water boxes have division plates to bring the coldest inlet water into thermal contact with the coldest air. By removing the water-box covers the whole of the tubes may be cleaned on the water side and re-packed without breaking any pipe joints. To facilitate this removal, swinging arms may be included.

In early installations the cooling water supply was taken from a tank, the head being less than the air pressure to ensure that moisture was not carried over to the alternator windings in case of cooler leakage. Experience has shown that special precautions are not necessary to prevent moisture being carried over to the windings. The possibility of tube or joint leakage is very remote as the individual tubes are subjected to a hydraulic pressure test of 600 p.s.i., and the completed air cooler is tested to 30 or 40 p.s.i. These tests ensure that no faulty material is used and that all the joints are perfectly sound.

Data relating to a number of typical coolers are given in Table 53, and the areas allow a reasonable margin for tube fouling, etc.

TABLE 53. *Air-cooler Data*

M.C.R. of Alternator	20 MW 6·6 kV.	30 MW 33 kV.	30 MW 11·4 kV.	50 MW 11·4 kV.
Surface area square feet .	5,400	7,000	16,000	9,700
Cooling water, gallons per minute . . .	700	550	750	1,100
System and ° F. . .	River, 50	River, 60	Cooling tower, 90	Cooling tower, 90
Air entering cooler ° F. .	100	135	146	160
Air leaving cooler ° F. .	74	85	105	102

The tubes are usually ½ to ¾ *in.* external diameter and 22 to 19 S.W.G. Either 70/30 brass or 70/29/1 admiralty mixture.

Fans and Blowers. Some makers prefer the cooling air to be circulated by separate motor-driven fans, others a combination of separate fans and integral rotor fans, whilst quite a number of even larger sets are fitted with only integral rotor fans.

The advantages of independently driven fans compared with fans on the rotor shaft are :—

(1) Improved efficiency of fans.

(2) Air supply to the alternator can be adjusted to suit the load by driving the fans with variable speed motors or alternatively by partially closing the dampers in the discharge ducts. Considerable saving may be thus effected when a set is run on light loads for appreciable periods.

(3) The overall length of the alternator is greater where fans are fitted on the rotor.

(4) High-speed fans are liable to be noisy and may be difficult to balance and also interfere with the fixing of balance weights on the rotor.

(5) Independent fans due to their higher efficiency heat the air less than rotor fans. This difference may be quite appreciable for the losses in the fans on the rotor represent an appreciable percentage of the total losses in the alternator.

(6) High-speed rotor fans necessarily consist of a number of highly stressed parts and the failure of such fans is much more serious than the failure of separate fans as they may damage the stator end-windings and even lead to the destruction of the alternator.

The integral fans should be of substantial construction consisting of heavy-gauge blades riveted to forged steel rings, being securely bolted to the face of the adjacent rotor endplate. In very large sets a separate blower direct-driven from the alternator is sometimes employed. Motor-driven fans are mounted inside the alternator

foundation block, the motors alone being external to the foundations though the fan bearings are accessible. A large amount of space is saved in the basement and the path of the air flow is improved. Two half or three-quarter capacity fans operating in parallel are usual. A fan fitted on the end of the rotor is useful during periods of light load when the motor-driven fans may be switched off. Taking the case of a 30 MW set, three makers had different methods of ventilation :—

(1) Two 50 per cent. external motor-driven fans.

(2) Two fans mounted one on each end of the rotor.

(3) Two fans mounted one on each end of the rotor together with two external motor-driven fans. The system is arranged so that with the alternator operating continuously at 80 per cent. of the maximum continuous load, one of the external fans may be shut down and at 50 per cent. of the maximum load both the external fans may be shut down.

Dampers are fitted in the ducts to re-direct the flow of air when the integral fans alone are in operation. A damper is fitted in each fan outlet so that it is possible to vary the load on either fan or isolate a fan from the system. Dampers should not be partially closed or a fan taken out because of low load on an alternator unless the kVA. output is in line with the makers' requirements. Restricted air flow under such conditions may result in dangerous hot-spots in the stator windings. Similar conditions may arise when dew-point is reached on air cooler and a fan is taken out in the hope of preventing moisture deposits on the cooler. A direct-driven blower is very reliable and efficient but the overall length of the set is considerably increased. The fans located in the foundation block should be accessible whilst their design and construction should be such as to facilitate inspection and maintenance. Where two fans are placed in line with little clearance, the bottom halves of the bearings should not be integral with the supporting pedestals, otherwise a faulty bearing cannot be removed without entailing withdrawal of the fan shaft, and consequently the motor. Ball and roller bearings appear to be quite suitable for the driving motors running at the usual speeds. Trouble has been experienced with ball and roller bearings on fans probably due to vibration and hammer effect. This is very pronounced when one motor is running and the other is stationary, the bearings of the latter being damaged due to the vibration and hammer action. There has been frequent trouble with higher speeds of 1,470 r.p.m. or thereabouts, but with lower speeds up to 960 r.p.m. the fan bearings are apparently trouble

free. Good concrete foundations should always be provided if trouble-free service is to be maintained.

The exciter can be totally enclosed and ventilated by means of a fan on the shaft, the cooling air being drawn from the alternator supply and returned to the cooler. The quantity of cooling air required will, of course, depend on the output of the alternator and the design of the cooling system ; the corresponding quantity may vary from 13,000 ft.^{3} per minute for a 3 MW set to 120,000 ft.^{3} per minute for an 80 MW set. The quantity of air in circulation is about 70 to 85 ft.^{3} per minute per kW. loss whilst the water quantity is usually about 0·8 g.p.m. per kW. loss. The figures differ for almost every maker, *e.g.*,

75,000 ft.^{3} with air inlet to cooler 146° F.
44,000 ,, ,, ,, ,, ,, 152° F.

Estimating the losses by the temperature rises of the air shows that these account for about 90 per cent. of machine losses in first case and only 60 per cent. in second case. This would appear to indicate that frame cooling is relied upon for about 30 per cent. of the total losses.

A typical example is given :—

An alternator delivering 50 MW has an efficiency of 97·5 per cent. at 0·8 power factor. The cooling air is supplied by two external motor-driven fans, the air entering at a temperature of 102° F. and leaving at 160° F. Fan-water gauge is 10 in.

Constants required :—

One kW. hour	3,412 B.Th.U's.
Volume of 1 lb. of air . .	13 cubic ft.
Specific heat of air . . .	0·24
Weight of 1 cubic ft. of water .	62·3 lb.

$$\text{Total losses} = 50{,}000 \times \frac{2\cdot5}{97\cdot5}$$
$$= 1{,}280 \text{ kW.}$$

Theoretically the alternator and exciter bearing losses (mechanical) should be deducted from this figure, but they are relatively small and can be neglected. Assuming cooling air to carry off all this heat then the quantity of air necessary can be calculated from :—

Heat per minute $= W_a (T_2 - T_1) k_{p.a.}$

Where W_a = weight of air in lb. per minute.

T_2 = final temperature of air.

T_1 = initial temperature of air.

$k_{p.a.}$ = specific heat of air.

Substituting the values given, we get :—

$$\frac{1,280 \times 3,412}{60} = W_a (160 - 102)\ 0.24$$

from which W_a = 5,250 lb. per minute,
or Q_a the quantity of air per minute.

$$= 5,250 \times 13$$
$$= 70,000 \text{ ft.}^3 \text{ approx.}$$

If the loss due to brush friction and the dissipation of heat from the machine casing, etc., then the quantity of air required would be slightly lower than this figure. A figure of 10 to 15 per cent. could be allowed.

If two fans be adopted each would be capable of delivering 35,000 ft.^{3} per minute. When operating independently it is sometimes desirable that each fan be able to deliver about 75 per cent. of normal full load in which case the total air to be dealt with by each fan per minute

$$= 70,000 \times \frac{75}{100} = 52,500 \text{ ft.}^3$$

The theoretical work done = PV ft.-lb.
Where P = pressure in lb. foot.^{2}
V = volume of air in ft.^{3}
Now fan-water gauge required is 10 in.
Pressure = density × head

$$= 62{\cdot}3 \times \frac{10}{12}$$
$$= 52 \text{ lb. per foot.}^2$$

or 1 lb. per square inch = 2·3 ft. head.

$$\therefore \frac{10}{27{\cdot}6} \times 1 = 0{\cdot}364 \text{ per inch.}^2$$

$$\text{or } = 0{\cdot}364 \times 144 \text{ lb. per foot.}^2$$
$$= 52 \text{ lb. per foot.}^2$$

$$\text{H.P.} = \frac{52 \times 52,500}{33,000}$$
$$= 83 \text{ approx.}$$

Assuming a fan efficiency of 75 per cent. and a driving motor efficiency of 93 per cent. then the

$$\text{H.P. required} = 83 \times \frac{100}{75} \times \frac{100}{93}$$
$$= 120$$

(110 B.H.P. for each motor).

One 30 MW set has 2 fans each having a capacity of 27,500 ft.^{3} per minute and 14·5 in. W.G. pressure inlet air 80° F.
Air cooler face area 63 ft.^{2}

Average velocity 1,000 ft. per minute with 2 fans (*a*).
,, ,, 760 ,, ,, ,, 1 fan (*b*).

Quantity $= 1{,}000 \times 63$
$= 63{,}000$ ft.^{3} with 2 fans (*a*).

Quantity $= 47{,}880$,, ,, 1 fan (*b*).

(*a*)	Pressure at each fan outlet	7·6 in. W.G.
	Fan inlet	6·4 ,, ,,
(*b*)	Pressure at fan outlet	3·8 ,, ,,
	Fan inlet	4·0 ,, ,,

Ducting and Doors. The ducting is made of mild steel sheets which are arranged inside the foundation block. Emergency air inlet and outlet doors are included which are operated in case of failure of cooling water or air supply. These doors are also useful when the set is being run up for drying-out when they can be opened at regular intervals to ensure there is no stagnation of damp air in the air system. Wire screens or guard rails should enclose the door openings if the doors are in such positions that, when opening, they endanger the operatives.

Brush-Ljungstrom Alternators. The stator windings are connected in parallel and the rotor windings are connected electrically in series to an exciter as shown in Fig. 408. The rotors are mechanically coupled direct to each half of the turbine blading system.

On starting up, the two rotors will not necessarily accelerate equally, but when about half-speed is reached the exciting current attains a value sufficient to cause the two rotors to synchronise automatically. The main field ammeter may swing over a wide range until this point is reached but when the two rotors synchronise the pointer becomes steady and the set can then be run up to full speed. The question of electrical unbalance does not appear to have been experienced. The two sides are very nearly the same and the power generated by both sides is almost identical. The limiting condition is when one of them is idle and one alternator only is driven and this never obtains in practice.

High-voltage Alternators. Reference has already been made to high-voltage alternators and the advantages justifying their use. The voltage now employed is 36 kV. although 66 kV. is possible should a system justify its adoption. The core conductor slots are

proportioned so that the internal reactance of the set is high and almost equal to the value obtained in an equivalent combination of low voltage alternator and transformer. An important consideration in the design of the high-voltage alternators, which are connected direct to the system network without step-up transformers, is the provision of adequate insulation between adjacent turns of the winding. The insulation may have to withstand more severe

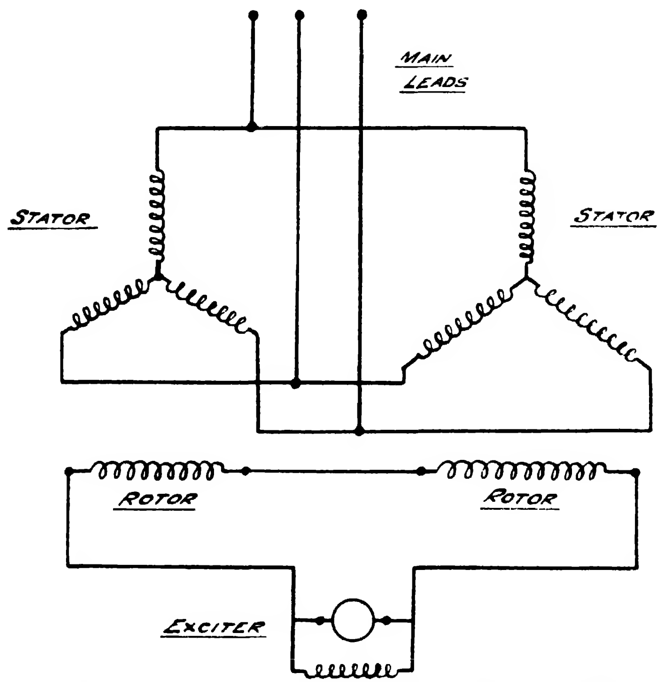


FIG. 408. Diagram of Connections of Brush-Ljungstrom Turbo-alternator.

surge voltages than a lower voltage machine, since any surges originating on the network, parts of which may be overhead line and exposed to lightning storms, will impinge directly on the stator end windings. Another problem is the prevention of corona due to the high-voltage gradients which may occur in the air spaces between adjacent coils in the end windings. Corona in association with air and moisture may cause the formation of nitric and similar acids, which in time will destroy the insulation. There are two types of winding in use—the first employs the standard method of winding used on lower voltage machines, but with improved quality and

greater thickness of insulation, while the second uses a special concentric conductor. Alternators have been built utilising insulation to earth which is graded in thickness from the neutral to the high-voltage terminals. Whilst a construction of this type is permissible with an adequately earthed neutral, many extra-high-voltage alternators run with an isolated neutral. Under such conditions dangerous surge potentials can be created on the comparatively lightly insulated section of the winding adjacent to the neutral point. Fig. 409 illustrates the two types. The insulating materials used are chiefly mica and asbestos.

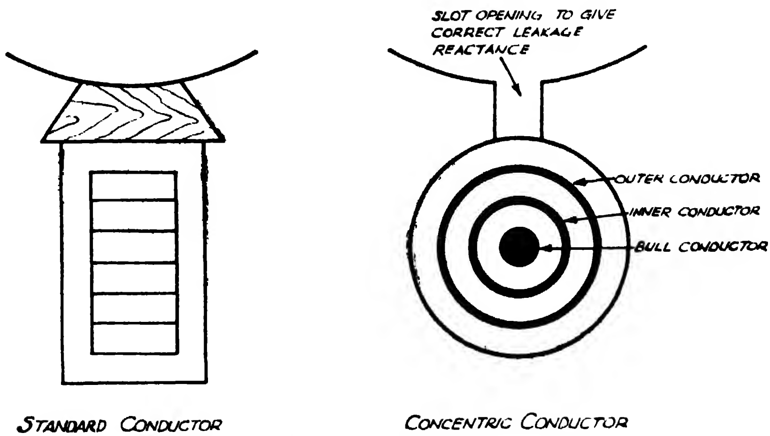


FIG. 409 Types of Conductor.

In one design the conductors forming the stator windings are similar to the cables used for electrical work except that mica or micanite is used for their insulation instead of paper. The conductor consists of three circuits forming what are known as the outer, inner and " bull " conductors. The central or " bull " conductors of each phase are connected in series, then to the surrounding " inner " conductors and finally to the " outer " conductors again in series. The phase-ends of the outer conductors are joined at the neutral point (Fig. 410). In an alternator generating at 36 kV. between lines, the phase voltage is 21 kV., this being the maximum voltage to earth. The potential of the " bull " conductors to earth ranges from 21 to 14 kV., that of the " inner " conductors from 14 to 7 kV., and that of the " outer " conductors from 7 kV. to zero. With the concentric arrangement, the insulation between conductors is called upon to work at a potential difference of less than

7 kV. and this is the maximum voltage between the outer conductor and earth with the alternator generating at 36 kV. The concentric conductor is inherently and adequately protected against

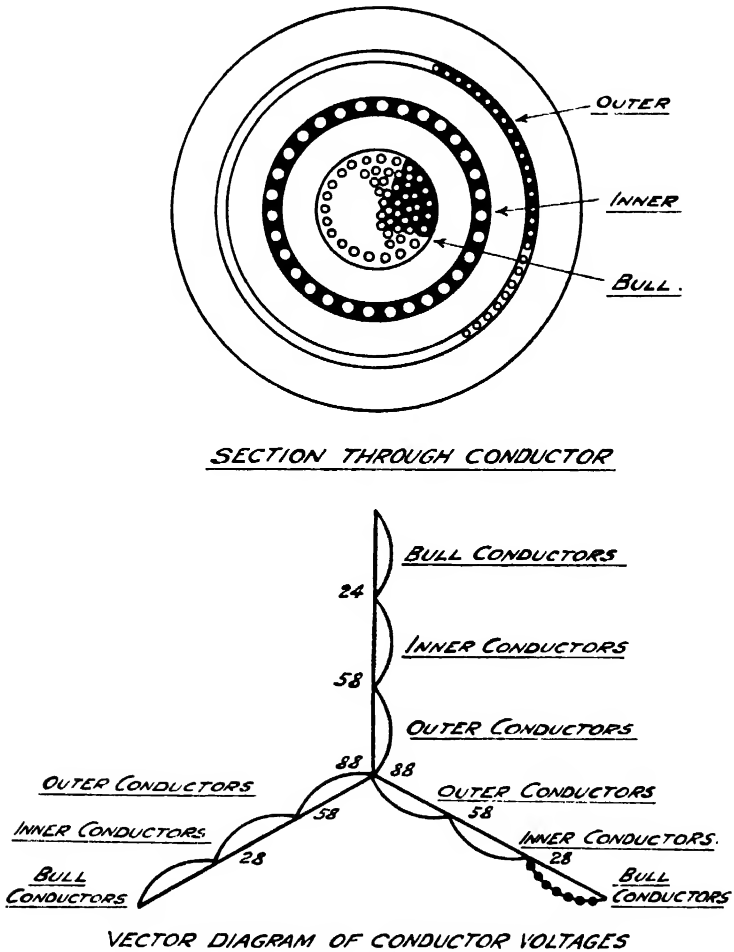


FIG. 410. High-voltage Windings (C. A. Parsons).

voltage surges. This is due to the high capacitance between sections of the winding forming a direct path to earth for a surge. Further, as opposed to the small values obtained in non-concentric windings this capacitance is high compared with the electrostatic capacity of the turns to earth, and for this reason a surge voltage,

even with a steep wave front, is uniformly distributed across the winding from the "bull" conductor to earth. The transient voltage between sections and between turns is thus kept down to a moderate figure. The lines of electrostatic flux are all radial and the insulation is therefore operating under the best possible conditions. It is not convenient to continue this simple construction through the end-winding on account of the bending difficulties, and each of the conductors must here be brought out separately. Comparing the two methods of winding the concentric conductor arrangement gives the best slot conditions but a difficult end-winding, whereas the standard winding gives slightly less favourable slot conditions but a somewhat simpler end-winding. The stator conductor bars are in the form of three-core concentric cables, made of wire stranded in the usual way but having micanite insulation around each core. The individual wires of the core conductors are insulated and spiralled in a definite lay to eliminate eddy currents while the conductors themselves are insulated with machine-wrapped tubes of micanite. Each conductor, after being impregnated with varnish and dried out is tested to nearly five times the normal working voltage ; the dielectric losses of the insulation are also checked. The end-windings, which are of copper rod, are arranged in nine banks : in groups of three, one for each phase. They are rigidly supported with moulded mica and wood packing, and firmly held with non-magnetic supports.

When the jointing and insulating of the stator windings is completed the whole of the end-windings are impregnated in a special high vacuum pressure impregnating plant. During the drying-out process under vacuum, the air pressure is reduced to 2 or 3 mm. of mercury by means of a special pump, after which the impregnating varnish is admitted into the main chamber and a pressure of 30 lb. per square inch is applied for some hours. The elimination of all air spaces ensures the utmost reliability of the machine. The forces on the end connections of a high-voltage alternator due to short-circuit are about one-quarter of those in the corresponding low-voltage alternator. For an 11 kV., 30 MW alternator the forces in the end connections between phases is 90 lb. per foot run, while for a 36 kV. alternator of the same output the force is only 21 lb. per foot run. These figures assume that the high-voltage alternator is short-circuited directly across its terminals while the low-voltage alternator is short-circuited across the high-voltage terminals of its step-up transformer.

General. There are a number of installations where combined high and low pressure turbo-alternators are run as a unit and Fig. 411 shows diagrammatically such a layout. The two alternators can be run independently but a special exciter is required when they are to be started up as a single unit.

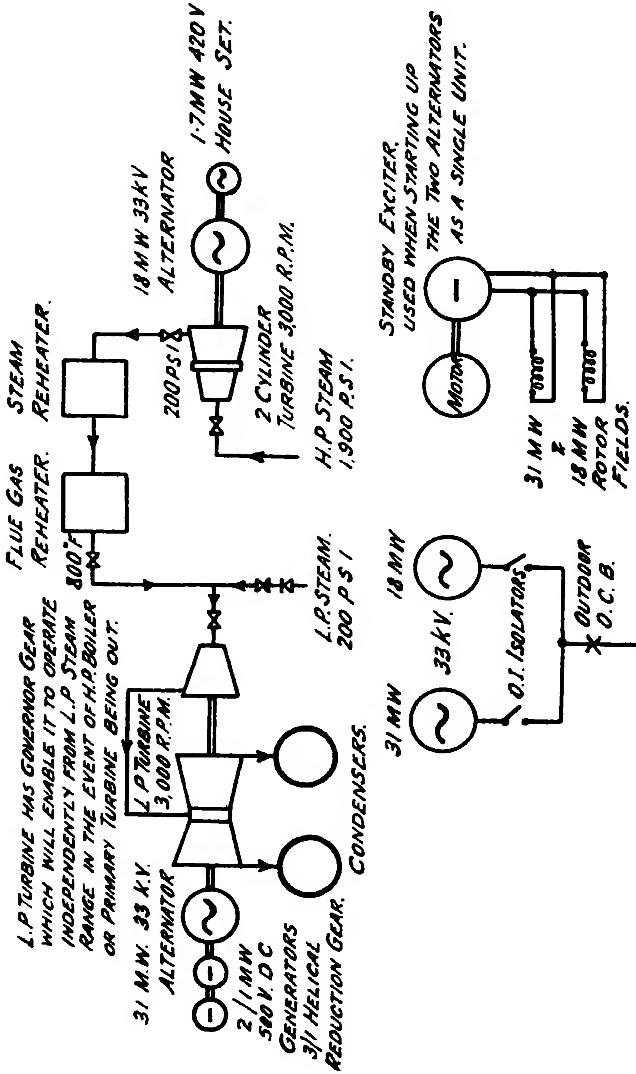


Fig. 411. Layout of Combined HP/LP Turbo-alternators.

It is sometimes necessary to run an alternator uncoupled from its turbine, *e.g.*, to prove balance, etc., and the procedure to be adopted will be followed by reference to Fig. 412.

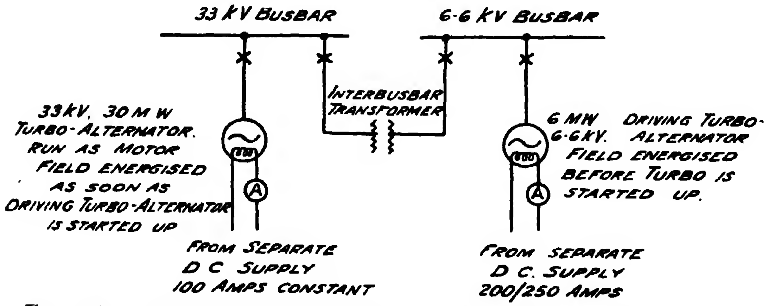


FIG. 412. Arrangements for running Turbo-alternator from Main Bus-bars.

units. It is enclosed in a tank and immersed in oil, the tank having radiating fins or circulating tubes around the outside through which the oil circulates naturally, thus appreciably increasing the area of the cooling surface. With oil-immersed forced-cooled transformers the cooling medium may be either air or water. The standard practice in this country is to employ external cooling.

TABLE 54. *Methods of Transformer Cooling*

Method of Cooling	Type	Abbreviation
Natural cooling	(*a*) Oil immersed natural cooling	O.N.
Artificial air cooling (with air blast).	(*a*) Oil immersed air-blast cooling (*b*) Oil immersed forced oil circulation with separate oil cooler and air-blast cooling.	O.B. O.F.B.
Partial artificial cooling	(*a*) Oil immersed natural cooling for a predetermined output with air blast. (*b*) Oil immersed natural cooling for a predetermined output with forced oil circulation with separate oil cooler and air-blast cooling above this output.	O.N./O.B. O.N./O.F.B.
Artificial cooling (with water circulation).	(*a*) Oil immersed water cooling (*b*) Oil immersed forced oil circulation with separate oil cooler and water cooling.	O.W. O.F.W.
Natural cooling (Part)	(*a*) Oil immersed forced oil circulation.	O.F.N.

The cooling equipment consists of :—(1) Oil cooler unit ; usually of the radiator type excepting when water cooling is adopted. (2) Oil pump and pipework. (3) Air blowers and ducts.

More space is required to accommodate the radiator and air-blast methods than with water cooling. When the latter is employed, cooling water may be taken from the circulating water system, or in emergency from reserve water tanks or town main. The water pressure in the cooler should be kept below that of the oil to prevent possibility of leakage of water into the oil system. The necessity for auxiliary power and periodic attention, together with the risks involved to the transformer itself should the cooling plant fail, has encouraged the use of self-cooled transformers in large sizes even though they cost more than forced-cooled transformers. Air-blast cooling by fans can be added to natural cooled transformers and so increase the output by some 20 to 30 per cent. The forced oil natural cooling system (O.F.N.) is useful where for reasons of

space the radiating surface has to be some distance from the transformer. The oil is pumped round the cooling system, from which radiation is by natural air. Fig. 413 shows the comparative cost for various methods of cooling and Figs. 414 and 415 indicate the usual cooling systems.

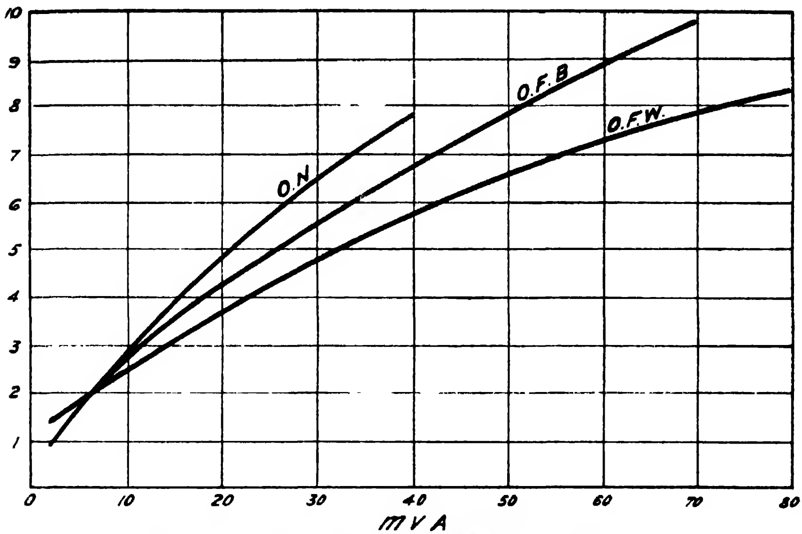
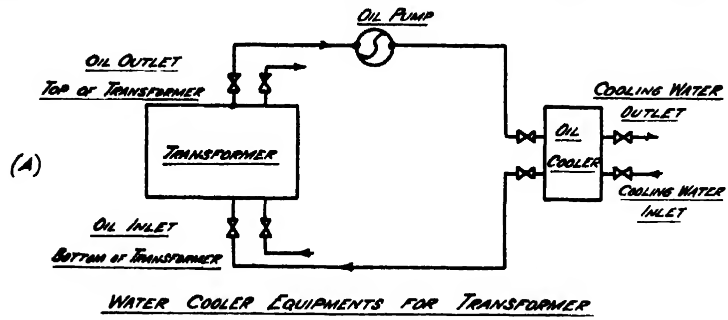


FIG. 413. Comparative Costs of Methods of Cooling.

Sizes. The outputs of the units depends upon the loadings of the sections of plant which they serve. The main step-up transformer will usually have an output equal to that of the alternator. The output will determine the sizes of the transformers and this will have a bearing on the floor and building space required to house them. The question of transport also has to be borne in mind for units of over 100,000 kVA. have been built for station working. The limiting feature was transport, but with the advent of improved handling equipment it is possible to transport by road or rail any size of unit contemplated. The overall heights of transformers, particularly the large units, may be reduced by employing a five-limb core in place of the more usual three-limb construction. By limiting the height of the core limbs it is necessary to reduce their sectional area to accommodate the requisite number of turns and to compensate for this reduction in core section it is necessary to provide other parallel iron circuits to maintain the flux density within prescribed limits.

Layouts. A problem which repeatedly confronts the station designer is whether the transformers should be housed or placed out



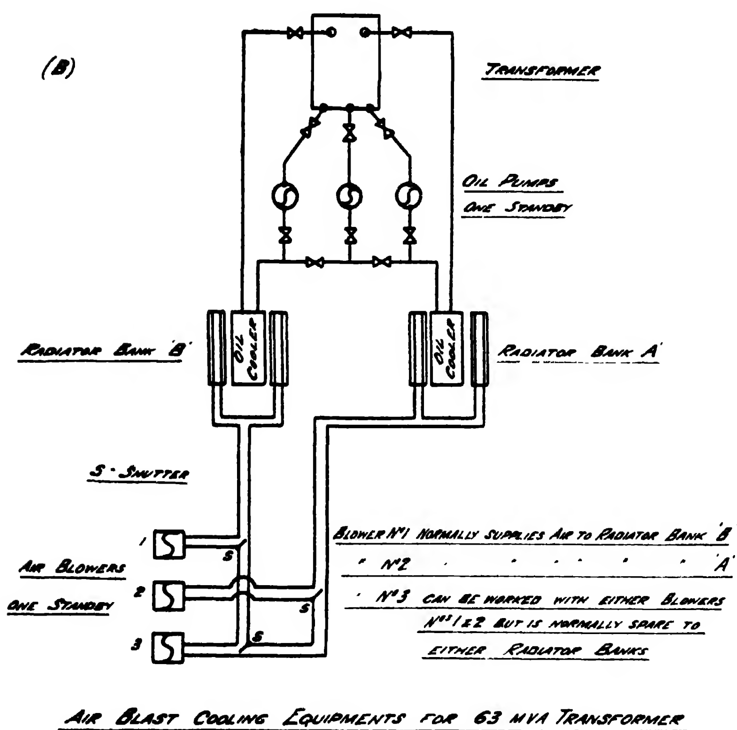


FIG. 414. Typical Diagrams of Transformer Cooling Systems.

of doors. With indoor working the cost of the transformer is rather less, maintenance can be done under more favourable conditions

and there is protection from the weather, etc. Standby outdoor transformers should be energised during winter months to prevent deterioration of the oil whereas indoor units can remain switched out if one unit is on load or radiators are installed. With outdoor working buildings are unnecessary, excepting foundations and fire sectioning walls. Outdoor transformers with outdoor bushings, supporting insulators and copper connections require more maintenance, particularly in industrial areas, also a larger ground area. It may be necessary to erect protecting screens and tape the connections to prevent accidental contact from birds and wind-swept twigs and branches, etc. Arcing horns or metal extensions may be fixed to the line and earth fittings of the bushings and insulators and be shaped and located so that when arc-over occurs it will

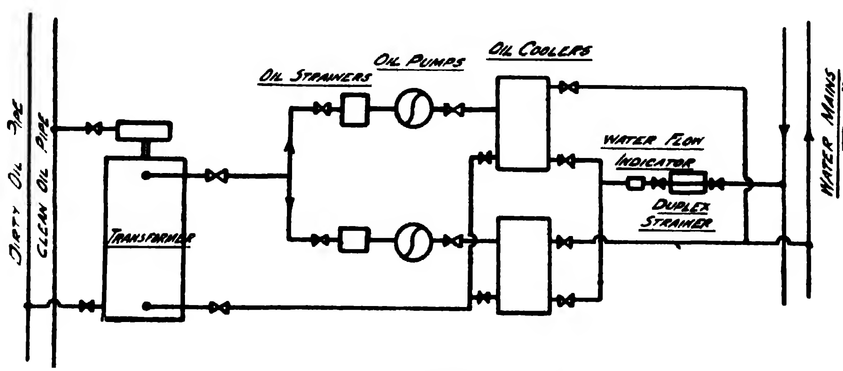


FIG. 415. Oil Cooling Water System for large Transformer.

be between the horns and not over the surface of the insulator. Filling material is usually employed for the spaces between the internal insulation and the weather-protecting shell, and provision made for thermal expansion of the filling medium.

Conservators are fitted on outdoor transformers and in some instances on indoor types where the conditions are justifiable, *e.g.*, in boiler-houses. When transformers are placed in bays between switch houses the walls of the latter produce a flue effect and so draw off the heat. The transformers should be arranged so that a faulty unit does not endanger its neighbours in case of explosion or ignition of oil. When transformers of the indoor type are used they are placed in individual brick or concrete cells. A brick well should surround all indoor transformers ; a height of 18 to 24 in. appears to be ample for units up to 1,000 kVA. but will

have to be increased to suit the oil content of larger units. Probably 4½–9 in. brickwork or curbing would meet the requirements. These wells may be filled with pebbles to a height not exceeding the lower ends of the cooling tubes. In the case of outdoor units these can

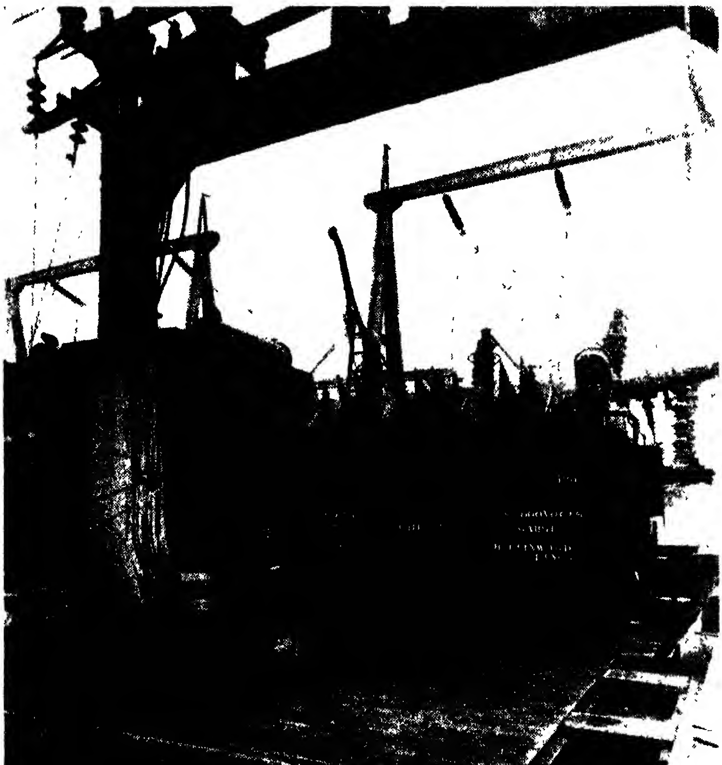


FIG. 416. 75 MVA, 3-Phase 132/33 kV. Outdoor Transformer. Self-cooled rating of 45 MVA. Full rating obtained by means of forced-oil circulation and air-blast cooling of the radiators. On-load tap-change gear is fitted to the higher-voltage windings giving electrical remote control over a range of 20 per cent. voltage in 14 steps. (Ferranti & Co. Ltd.)

be spaced and an additional precaution taken by building walls between and around the units (Figs. 416 and 417). These walls should be at least 9 in. thick and built to extend just above the transformer bushings or tops of the cooling tubes, thus affording protection in case of explosion and consequent fire on adjacent

units. Dwarf walls may be provided for end transformers and also the front of centre transformers. Weep holes should be included in the dwarf wall to allow rain water to leak away. Where large transformers are installed it is necessary to provide ample drainage to soakaway pits around the units. The pits should be of such size that any leakage of oil up to complete rupture of the tank is led away and effectively quenched. Usually some straining medium

FIG. 417. Two 10,000 kVA., 33/6·6 kV. Three-phase Transformers. The cooling radiators are in similar compartments beyond the transformers. "Mulsifyre" fire-fighting equipment is also installed.

such as pebbles, granite chippings, sand or chalk laid in connecting ducts and drains will suffice. The methods of filling the main sumps vary considerably; one authority has suggested :—

Bottom section to consist of chips					2 in. dia.
Middle	,,	,,	,,	,,	1–1½ in. dia.
Top	,,	,,	,,	,,	½ in. dia.

Other suggestions are a mixture consisting of 50 per cent. 2-in. mesh and 50 per cent. ½ in. mesh pebbles, or alternatively sand filling only. The surfaces of surrounding soakaway areas should be kept free and not allowed to become clogged due to the accumulation of dust, etc. The subject of fire protection has been very much

to the fore and although it is a matter of experience that the transformer is almost immune from trouble causing fire, nevertheless the spreading of burning oil from a damaged transformer calls for consideration. Transformers of reasonable output are usually fitted with explosion diaphragms and these afford protection against tank failures. Consideration should be given to the layouts for access and handling for unloading, inspection, and maintenance ; this applies particularly to the step-up and larger auxiliary units. There is one point deserving care regarding the maintenance of main transformers on cooling tower station sites and that is they should be situated on the side of the prevailing wind, otherwise special waterproof canopies will be necessary during overhaul when tap-change oil tanks are opened. Flash-over of insulators has also occurred and for use in a highly polluted and humid atmosphere a leakage path of 2 in. per kV. of applied voltage is found to cover most cases. Particular mention should be made of transformer stations in the vicinity of cooling towers using sewage effluent. Here it is possible to get wind-blown froth which forms deposits on the insulators, sets very hard and is difficult to remove. This hard sediment may cause flash-over, particularly when chlorine treatment is used in sewage effluent make-up cooling water. If the transformer annexe adjoins the turbine house the overhead crane can be used for lifting purposes. Three methods of handling are :—

(1) Fitting transformers with swivel-flanged wheels allowing them to be shunted to their positions. If the units are on a concrete raft or plinth provision is made to enable them to be jacked up whilst the wheels are being turned.

(2) Providing a special truck having rails laid transversely across its deck at the required height.

(3) Unloading the transformers off a special rail track designed to spread the load.

The transformers may have rollers, wheels, skids or jacking bosses according to the site and methods of handling available. In deciding upon the method the site conditions should be investigated to avoid heavy concentrated loading and danger of fouling rail points, etc. The manœuvring of large transformers calls for special attention, and in restricted spaces recourse has been made to spraying of oil on the roadway and slewing the vehicle round by tugging it with a tractor. Where residential property is in the vicinity of transformer banks care should be taken to minimise the

emission of noise. The principal design factors in reducing the noise level are a reduction of the flux density and a substantial and well-clamped core; a further precaution is the inclusion of anti-vibration pads between the transformer and its foundations. Rubber of suitable proportions and loading has proved satisfactory. Pads consisting of sandwiches of cork and lead also effectively damp out any noise due to transmitted vibration. The foundations may be sectionalised by the inclusion of strips of bitumen filling which tends to prevent transmission of noise. Alternative methods of preventing direct emission of noise are to house each unit in a massive brick or concrete chamber the entrance of which is finally closed up, or, completely surround the transformer tank with sound-absorbing material.

Special Units. An auto-transformer is employed for providing the voltage variations which may be required on electrostatic precipitation plants. It is arranged to give 50 per cent. variation in L.T. voltage and likewise a similar variation in H.T. voltage. Single-phase air-cooled types are usual, being wound for 600 volts with some twenty taps between 300 and 600 volts. The step-up transformer has a ratio of 1 to 100 and is of the oil-immersed self-cooled type with conservator and pressure relief pipe. The three-legged core has only the centre leg wound and both ends of the high tension winding brought out to porcelain bushings of the compound filled type. The H.T. winding is insulated for full voltage as both ends are alternatively earthed and connected to the precipitator end of the rectifier. The insulation is reinforced to withstand the high frequency surges which may be set up by the precipitator.

The interconnected-star transformer for neutral earthing has certain advantages, some of which are :—

(1) It will supply an unbalanced load with very little voltage unbalancing.

(2) The star-interconnected star winding has electrical characteristics similar to the delta-star transformer and can be paralleled with it.

(3) A neutral point is available on the primary and secondary sides, only one of which should be earthed.

(4) Due to the interconnection on the secondary side the voltage is free from third harmonic components.

(5) The interconnected star winding is useful for providing a neutral point on an insulated system. Thus with an interconnected star-star transformer the neutral point of the primary may be used for giving an earthing point for the system, and has the advantage that as the reactance of the interconnected star windings is low it provides a low independance path for the flow of single-phase earth fault currents. The secondary star winding may be used for three-phase supply to station auxiliaries.

Without the secondary star winding it is usually termed an interconnected star (zig-zag) reactor (see Chapter XVIII.).

Design and Constructional Details. Transformers are of the core or shell types suitable for either indoor or outdoor service. The general practice is to design all transformers for operation with their higher and lower voltage windings each connected to a system the neutral of which is earthed, either direct or through resistance or reactance, or a combination of the two at one or more points.

The harmonic voltages should be suppressed to eliminate the possibility of high frequency disturbances, inductive effects or of circulating currents between the neutral points at interconnected power stations reaching such a magnitude as to cause interference with post office or other communication circuits. Where the high and low voltage windings of a transformer are connected star-star a delta connected tertiary winding is provided for this purpose. An even mechanical pressure over the whole of the core laminations should be maintained to prevent settling of the core during transport or in service and to eliminate noise and vibration in the core when the transformer is in operation. The framework and core bolts should be insulated from the core to reduce circulating currents to a minimum. The flux density in any part of the core usually varies between 11,500 to 14,000 lines per square centimetre at normal ratio. A reduction in flux density reduces the noise but entails extra cost. The latter is partly offset by the reduction in iron loss resulting from the lower flux density. Windings and connections should be free from insulating composition likely to soften, ooze out or collapse during all conditions of working. The materials used should not shrink, disintegrate, carbonise or become brittle under the action of hot oil when the transformer is operated continuously under all specified conditions of loading. Some examples of the types of insulation used are given in Table 55 (p. 191).

The majority of transformers are fitted with off-circuit voltage control, although in a number of installations some of the inter-bus-bar units have electrically operated on-load voltage control equipment. This equipment is arranged for both manual and remote electrical control. The manual control is placed near its transformer and interlocked with the remote electrical control so that it is impossible for the two controls to be in operation at the same time. Transformer tanks which are of welded sheet-steel construction should be designed to prevent the collection of moisture on any part and where troughs or cavities exist drains should be

TABLE 55. *Types of Insulation*

Insulation	66/6·6 kV.	11 kV./400 V.
Higher-voltage windings	Paper and press board	D.C.C.
Lower-voltage windings	,, ,, ,,	Cotton tape and elephantide
Tappings	Paper	Systoflex tubing or elephantide
Tapping connections	Paper	Bakelite tube or paper
Core bolts	Mica and paxolin tubes	Bakelite tube
Core bolt washers	Mica and paxolin	Elephantide
End plates	Press board	,,
Core laminations	Insuline	Varnish

included. It is possible during cable jointing operations, when the oil level is low, for damp air to enter a tank and become trapped which may reduce the dielectric strength of the oil.

A relief valve is provided in the cover of smaller transformers without conservators for the periodical release of any gas which may collect in the tank. This relief fitting is unscrewed when putting the transformers into service and replaced when taking them out for overhaul, etc. Transformers of larger output have a relief outlet fitted with a diaphragm of mica, bakelite or glass. This affords protection against tank failures due to explosion. When a Buchholz relay is fitted the relief outlet, or explosion vent, has two diaphragms fitted, one at the bottom of the outlet and the other at the top. In this way any gases produced must pass through the relay instead of being released to the relief outlet. Should the bottom diaphragm be ruptured (usually of paper) the oil then rises in the relief outlet and is clearly observed in the sight indicator fitted for this purpose. In some designs bubbles of gas rising from the transformer windings are not collected in the relief pipe, but pass straight up and are collected by a pipe which is fixed to the flat surface of a turret which leads direct to the Buchholz relay. With this arrangement no diaphragm is required at the joint between the tank and relief pipe. The top diaphragm is set to blow at a pressure of 5 p.s.i. Copper 0·01 in. thick is used.

An approved type of breather should be fitted to each conservator

vessel designed to ensure that :—(1) The external atmosphere is not continually in contact with the drying agent. (2) The passage of air is over the surface of the agent. (3) The moisture extracted

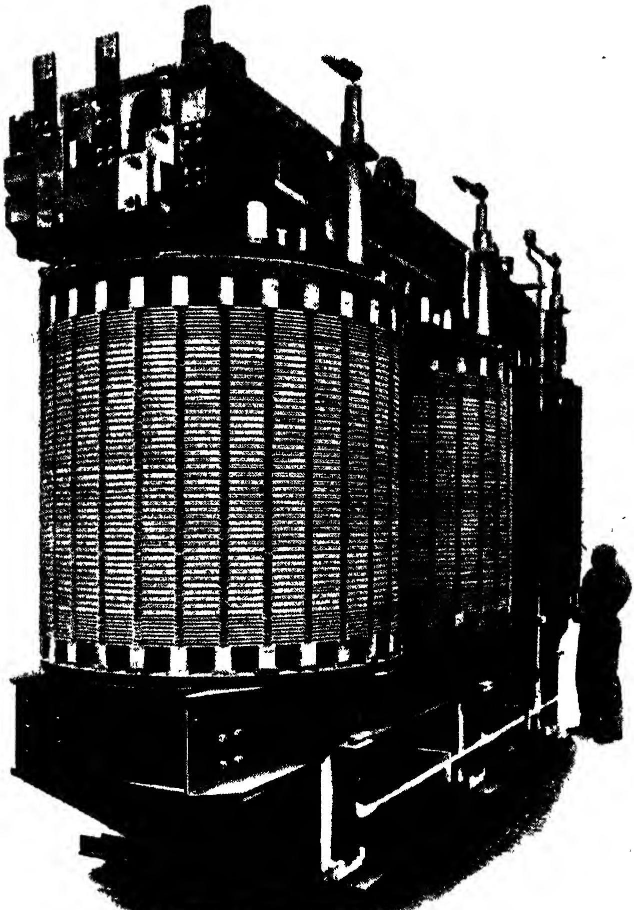


FIG. 418. 75,000 kVA., Three-phase 11/70·5, Delta/Star Type OFW, Untanked Power Transformer, showing H.V. Sides of Coils. (Metropolitan-Vickers Electrical Co.)

from the air has free passage away from the agent into a sump from which it can be drained. Calcium chloride was used as the drying agent in earlier days, but silica gel breathers are now standard. The oil connection between the conservator and transformer tank

should stand at least 1 in. high inside the conservator, so that any water which may condense in the conservator cannot enter the tank. A small drain can be fitted to empty this water trap.

The following are the usual accessories supplied with outdoor transformers :—(1) Silica gel breather. (2) Oil conservator tank. (3) Long oil gauge on conservator tank (circular gauge is also suitable). (4) Oil gauge on tap change tank and on other tanks containing oil, but separate from the main tank. (5) Diagram plate, name and rating plate. (6) Pressure relief valve. (7) Oil drain. (8) Thermometer with alarm contacts or thermometer pocket as required. (9) Provision for locking off all valves with padlocks.

For indoor transformers the accessories can be fitted as desired.

Tables 56 and 57 give comparative data for various sizes of transformers. Fig. 418 shows the internal constructional features of a large transformer.

TABLE 56. *Transformer Data*

Outdoor, output - kVA. (three phase-core type)		62,500	40,000	15,000	1,000	600	300
Normal voltage ratio		11,400 33,000	11,400 33,000	33,000 11,400	6,600 400	11,400 440	11,400 440
Type of voltage control		Off-circuit internal links (O.L. I.L.)	Auto on-load tap change	Auto on-load tap change	O.L. I.L.	O.L. I.L.	O.L. I.L.
Total weight . tons		125	133	53	5·8	3·8	2·65
Method of cooling		ON/OFB	O.N.	O.N.	O.N.	O.N.	O.N.
Fixed loss at normal ratio . watts		90,000	70,000	29,500	3,690	1,850	1,150
Load loss at rated kVA. and normal ratio. watts		470,000	250,000	115,000	11,400	8,750	5,000
Efficiency	$1\frac{1}{4}$ F.L. %	98·95	98·99	98·77	98·12	97·77	97 42
at	F.L. %	99·11	99·11	98·93	98·35	98·12	97·78
0·9 power	$\frac{3}{4}$ F.L. %	99 25	99·23	99·07	98·52	98 36	98 07
factor	$\frac{1}{2}$ F.L. %	99 34	99 27	99·14	98 57	98 53	98 25
Voltage	Resistance %		0·625	0·767	1 14	1·46	1·67
drop at	Reactance %	10·0	10·0	9·97	6·0	5·0	4·2
normal ratio	Impedance %	10·0	10·0	10·0	6·1	5·2	4·5

TABLE 56. *Transformer Data (continued)*

Regulation at rated kVA.	1·0 p.f. %	1·26	1·13	1·27	1·32	1·58	1·76
	0·8 p.f. %	6·9	6·8	6·9	4·6	4·25	3·88
Magnetising H.V. current at normal ratio amps.		26·2	7·0	2·6	1·75	0·80	0·38
Total oil required galls.		6,600	8,000	3,000	350	250	190

TABLE 57. *Transformer Data*

Output kVA. . .	62,500	40,000	15,000	1,000	600	300
H.V. winding square inch	0·92 & 1·04	0·389	0·084	0·035	0·0107	0·00575
L.V. ,, square inch	0·44	0·674	0·425	0·97	0·5	0·236
H.V. ,, C.D. amps. per square inch . .	2,120 & 1,880	1,800	1,800	1,650	1,660	1,530
L.V. winding, C.D. amps. per square inch . .	2,460	1,800	1,800	1,650	1,550	1,670
Volts, per turn . .	92	91	44	10·5	7·1	8·6
Weight of core and windings (interleaved core) tons	61·5	56·4	21·0	3·0	1·85	1·25

In the selection of a transformer for any particular service a number of factors have to be considered. The impedance of an alternator step-up transformer (140 MVA) was chosen at 8 per cent. after evaluation of transformer cost, losses, voltage regulation, system short circuits and effects on system stability.

A problem deserving careful consideration is that of the cable boxes. It is important that the boxes should be of adequate proportions to enable a large compound area to be maintained under all working conditions. Oil is often used on high voltage boxes and is not subject to voids as is the case with compound. Shrinkage takes place due to the fact that a certain amount of compound will over a period of time drain into the cable. This is more pronounced on transformer and reactor cable boxes as the conductors reach a fairly high temperature. Temperature variation causes expansion and contraction and in the process of contraction compound is drawn from the cable box into the cable. During the next process of expansion the compound is not pushed back into the box, but remains and swells the lead on the cable. The inclusion of a styrene

"plug" in single-core and three-core cables produces a barrier joint effect as far as migration of compound is concerned without introducing actual joints. An example is the inclusion of a styrene "plug" in the end of a tail cable leading from a transformer. This enables the transformer cable boxes to be filled with oil, working under the conservator system and eliminates troubles due to compound expansion, contraction, leakage, etc. An alternative to cable boxes is the use of brass glands for both the higher and lower voltage sides to enable cables to be taken straight into the transformers and wiped direct on to the glands. The glands may be arranged for the cables to be led out vertically or at an angle. If the cables are required to be run underground it is possible to loop the higher and lower voltage cables overhead in such a manner as to prevent syphoning of oil into the cables. Non-bleeding cables are used with these glands. All glands should be insulated from the tanks and cable boxes to withstand a test-pressure of 1,000 volts or over. On large transformers each cable box may be connected to the windings through an oil-immersed disconnecting flexible link housed in a separate chamber. This enables the transformer to be removed without interfering with the boxes and fixed cabling. Cable boxes may be filled with either compound or oil, the latter being used on higher voltages. The joints of cable boxes should be maintained in good order otherwise ingress of moisture will lead to trouble in the cable. Breathing is always taking place *viâ* joints, and after being in service for a time, especially in a humid atmosphere such as in the vicinity of cooling towers, moisture may find its way into the boxes. Fabricated (welded) boxes are susceptible to such troubles and special care is necessary. Hard rubber gaskets are not suitable for cover joints, but cork composition with a jointing mixture is satisfactory. Washers for screwed plugs are quite suitable if of hard rubber. Insulation tests will indicate any falling off in insulation, and cables may have to be replaced. Unless the joints are perfectly made and maintained in good order, considerable trouble may also be experienced due to leakage. This applies in particular to auxiliary boxes and tanks fixed to the transformer, and usually results in the cable compound being mixed with oil. Oil-proof compound has been used, and appears to be satisfactory. The oil used for transformers is either A30 or B30 and generally in accordance with B.S.S. No. 148—1951. In practice it is found that both classes have proved satisfactory. It is contended that class A30 transformer oil has contributed towards

breakdown due to increase in acidity during service. Class "B" oil is cheaper than class "A," and appears to be quite suitable.

Fire-resisting transformers, in which the whole of the insulating material used in their construction is non-ignitable are also in service. They are thus immune from damage which might be caused by short circuits or open circuits in the windings or breakdown in the major insulation. These transformers are capable of carrying very much heavier loads for longer periods than are normal oil-cooled or air-cooled units. In practice it is found that in general the B.S.S. overloads for oil-cooled transformers could be carried by fire-resisting transformers for periods between five to ten times those laid down in the specification. The transformers are air-cooled and can operate satisfactorily at temperatures of about 150° C. without damage or showing any deterioration in the insulating material. A number of these transformers are in service on voltages up to 11,000 delta and are giving satisfactory service. Provided some simple form of air circulation is applied, units of 3,000 or 4,000 kVA. could be economically made.

Natural air-cooled transformers of the "Berry" type consisting of three single-phase units have also been used up to 2,500 kVA. at 11 kV. More space is required, but the three units are housed in a sheet steel surround with drip-proof cover, ventilating openings being provided at the top and bottom. Oil acidity troubles and fire risk are eliminated and maintenance reduced, but the transformers are more costly.

Gas-filled transformers have been introduced in America in which nitrogen is used at a pressure of from 100 to 150 p.s.i.

Reactors. Reactors limit the current which may flow in a circuit under fault conditions and are of the air and iron core types. The air core reactor is constructed of several layers of stranded copper conductor with either porcelain or concrete separators. A constant reactance for all current values is obtainable with this type, and further, they are cheaper than iron core oil immersed reactors. On the other hand they are bulky and must be arranged with reasonable clearance from surrounding metal work, or trouble may arise with eddy currents set up in the metal work. Trouble due to vibration and heating was experienced on a 500-amp, three-phase bank (3 single air core reactors). Each reactor was enclosed in a cell having three brick walls, the top and front being expanded metal screens. The top screens were 6 in. from the tops of the reactors and the screens began to vibrate

and heat. On raising the side walls about 9 in. (giving a clearance of 15 in.) no further trouble was experienced. Air core reactors can be housed in chambers or cells adjoining the switchgear, but there must be adequate electrical clearances and the individual cells must be locked off. They have been used on voltages up to 33 kV. and proved quite reliable. Oil-immersed natural cooled reactors require less building space, are suitable for outdoor working and immune from external magnetic fields. With iron-clad reactors there are no external magnetic fields to cause heating of nearby steelwork or affect the accuracy of meters. Reactors of this type have been designed for a 3-phase rating of 7,500 kVA. corresponding to 12·5 per cent. reactance on 62,500 kVA. and operating at 66 kV., each 3-phase bank consisting of three separate single-phase reactor units accommodated in separate tanks. Three-phase oil-immersed reactors having a 3-phase rating of 3,750 kVA. corresponding to 10 per cent. reactance on 37,500 kVA. and operating at 11 kV. have been housed in a single tank, Fig. 419. Reactors should be designed to carry without damage for a specified time the maximum through short circuit current with the total kVA. available on the input side and have as nearly as possible a straight line characteristic up to this value of current. In the design magnetic saturation should be avoided under all fault conditions, otherwise the limits of protection are reduced. With windings of laminated or stranded conductors the strands are insulated to minimise eddy current losses. The insulation of the end turns and connections is reinforced and braced to withstand the effect of surges and switching transients. The windings may be either magnetically or electrically shielded to prevent stray flux entering any part of the coil clamping structure or tank. Laminated iron shields may be used when ratio of short-circuit current is less than 30 to 1 and copper shielding above this. The ratio between the normal current and maximum short-circuit current influences the thermal design of a reactor. If the reactor is to give 5 per cent. reactance and no other reactance is in the circuit, the short-circuit current is twenty times normal, in which case the short-circuit conditions probably determine the thermal design. But if there is additional reactance in the circuit so that the maximum short-circuit is only, say, twelve times normal, then normal load conditions have the greater influence on the design. This feature also has some bearing on the normal load loss and to reduce running costs it may be desirable to have a low load loss by the use of a larger

conductor which also improves the thermal conditions under short-circuit.

The voltage drop due to a reactor is dependent upon the power factor of the circuit since it is subtracted vectorially, at unity power factor the effect of the reactor is very small but as it decreases the effect of the reactor increases. The line voltage drop of a 5 per

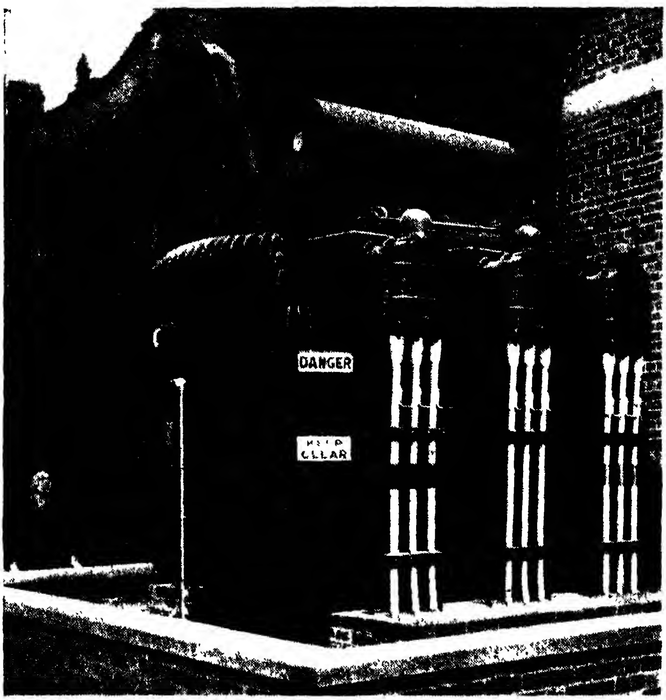


Fig. 419. Oil-immersed Magnetically Shielded Reactor, rated 3,750 kVA. 3-phase, 11,000 volt. Neepsond Power Station, Sheffield. (British Thomson-Houston Co. Ltd.)

cent. reactor at full load and unity power factor is about 3 per cent., i.e. $\frac{11,000.3}{100} = 330$ volts. If this is based on a throughput of 2,000 kVA. the kVAr. rating is $\frac{2,000.5}{100} = 100$ kVAr. The losses at full load are relatively low but when capitalised the figure can be quite considerable.

The following relate to a 33 kV. 6,250 kVA. (10 per cent. on 62,500 kVA.) 3-phase oil-immersed reactor bank :—

Maximum through short-circuit current to pass for fifteen seconds	10,930 (R.M.S.) amps.
Type of shielding.—Outside coils	Magnetic.
Over ends of coils	Non-magnetic.
Approx. through current to cause saturation of shields	11,000 amps.
Total sectional area of winding conductor	0·69 sq. in.
Size of each strand—width	0·32 in.
thickness	0·085 „
Current density in conductor and end connections	1,600 amps. per sq. in.
Insulation between strands	Paper.
Insulation between conductors and frame	Pressboard.
Total weight (single-phase unit)	10·5 tons.
Switchgear before reactor	1,500 MVA.
Switchgear after reactor	750 „

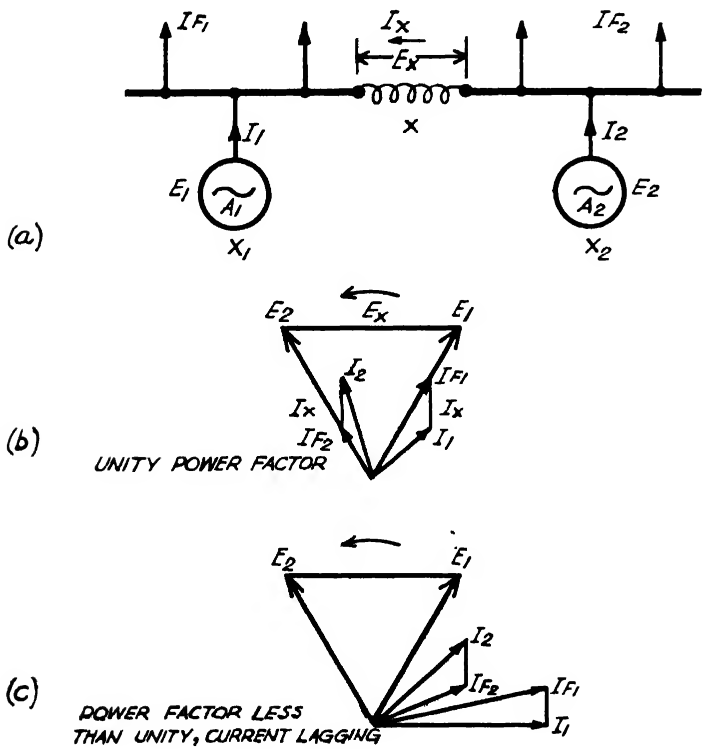
The fittings, etc., are generally similar to those supplied with transformers and reference should be made to B.S.S. 171/1936. Oil-immersed reactors require little or no attention and are not so prone to flashover and breakdown as the air-core type, although the latter have proved very reliable. The principles of transformer layout also apply to reactors.

Reactors in Bus-bars. The layout of the feeders on bus-bar sections should be such that at full load the interchange of current between sections is a minimum. During periods of light load when few sets are on the bars the reactors can usually be cut out of circuit since the fault current is reduced. If it is essential to transfer large currents from one section to another the reactances must be kept within certain limits otherwise the voltage drop across will cause difficulties in running. The bus-bar reactance must be the same as that of the combined alternator and transformer if the same degree of protection from fault current is desired. This will of course depend on the plant capacity connected to each section. The reactors between bus-bar sections limit the trouble to that section in which a fault occurs. They also result in the alternators being operated with a certain angular displacement. Another factor affecting the use of reactances is the effect on the rate of rise of recovery voltage after circuit interruption and careful proportioning of the reactance to the circuit capacitance is necessary to avoid neutralising the advantages accruing from the use of reactances.

Consider two alternators, A_1 and A_2, Fig. 420 (*a*), connected to feeder circuits F_1 and F_2, the bus-bars being split into two sections and connected through a reactor X. Assuming unity

power factor and the load on F_1 to be greater than F_2 and that the total load is shared equally between the two alternators, it follows that a certain amount of current must flow through reactor X. Neglecting the losses this current is in quadrature with the voltage across the reactor terminals. The vector diagram is shown in Fig. 420 (*b*), which represents the conditions for unity power factor, E_1 and E_2 represent the voltages of the two alternators and $E_1 . E_2$ the voltage across the reactor. I_{F1} and I_{F2} represent the currents in the two feeder circuits. The current flowing through the reactor is determined by the magnitude of $E_1 . E_2$ and hence the phase displacement of the alternators depends upon the difference in the loads in the two feeders. By subtracting I_1F_1 (at right angles to E_1E_2) in one case and adding I_2F_2 in the other, these two currents being the same, the currents delivered by the alternators I_1 and I_2 are obtained.

When the current is a lagging one, the conditions are shown by



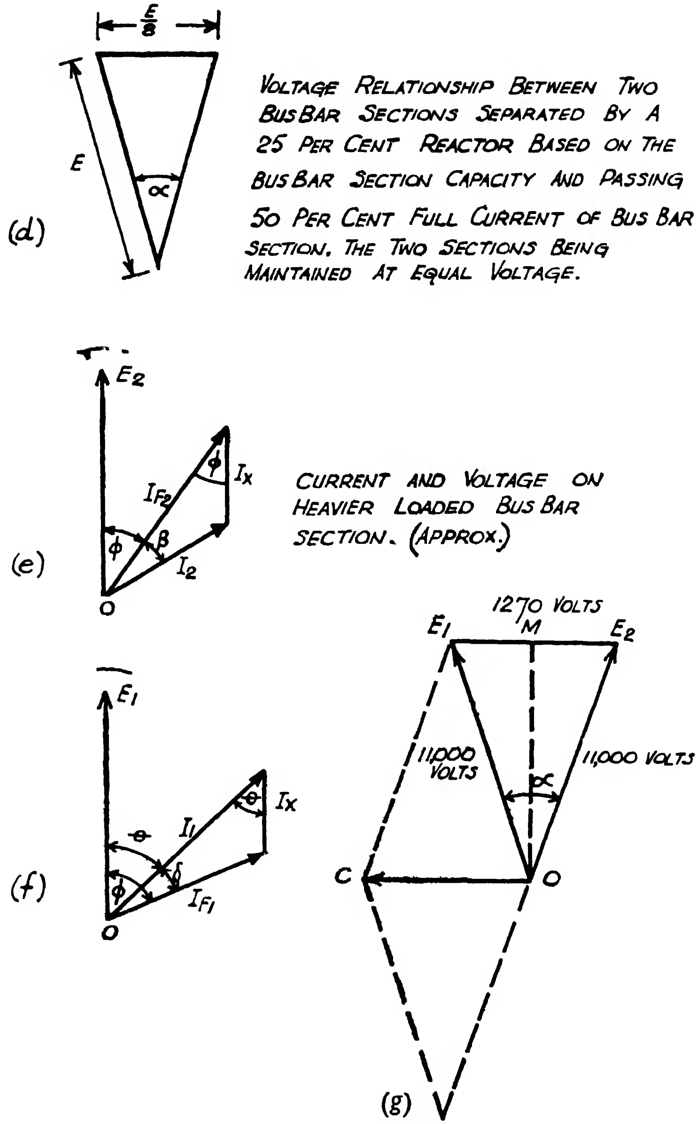


FIG. 420. (a—g). Effect of Reactor in Bus-bars.

Fig. 420 (c), the current $I_1I_{F1} = I_2I_{F2} = I_X$ flowing through the reactor being added to one alternator current and subtracted from the other to obtain the two feeder currents.

Considering a further example in which the maximum current that will ever pass through a reactor is 50 per cent. of the full load current of a complete bus section; also that the total reactance between each bus section is 25 per cent., reckoned on the total capacity of a bus section. The reactance of the alternators are X_1 and X_2 respectively and $X_1 = X_2$. The reactance between the two bus-bar sections = 25 per cent. Then with half-full load current flowing from A_1 to A_2 the volt drop across the reactor X will be E/8, it being arranged that bus-bar volts of A_1 equals bus-bar volts of A_2. Fig. 420 (*d*) gives the voltage conditions of the two bus-bars. The angle α is the phase difference between the voltage of the two bus sections.

By approximation $\sin\alpha = E/8/E$

$$= \tfrac{1}{8} \quad \therefore \alpha = 7^\circ.$$

To find to what extent the power factors of the respective alternators are altered under these conditions a power factor of the feeder load can be assumed. Assuming this to be 0·85, *i.e.*, $\cos\phi = 0{\cdot}85$ and $\phi = 32^\circ$. Referring to Fig. 420 (*e*), OE_2 represents the bus-bar volts of the A_2 bus-bar. I_X is the current flowing through the reactor, which can be drawn parallel to OE_2 for an approximate calculation as it lags 90° relatively to the voltage across it.

Then $\dfrac{\sin\beta}{\sin\phi} = \dfrac{I_X}{I_2}$.

If I_2 is, say, twice I_X,

$$\sin\beta = \frac{\sin\phi}{2} = \frac{0{\cdot}53}{2} = 0{\cdot}265$$

$$\beta = 15{\cdot}5^\circ,$$

Therefore the angle of lag of the current in alternator A_2 relative to the bus-bar volts is $32^\circ + 15{\cdot}5^\circ = 47{\cdot}5^\circ$

and the power factor at which the alternator A_2 is running is 0·68.

Considering alternator A_1, the approximate vector diagram is given in Fig. 420 (*f*).

I_{F1} is the current in feeders F_1 lagging 32° behind the bus-bar volts.

$$\frac{\sin\theta}{\sin\delta} = \frac{I_{F1}}{I_X}$$

$$\text{If } I_{F1} = 2I_X \text{ then } \frac{\sin\theta}{\sin\delta} = 2$$

and $$\theta = 2\delta \text{ approx.}$$

But as $\theta + \delta = \phi$ it will be seen that the angle of lag of the current in the alternator A_1 is about two-thirds of 32, *i.e.*, its power factor is 0·93.

In order to transfer current from the lightly loaded to the heavily loaded bus-bar, the power factor of the alternator on the lightly loaded bus-bar must be raised, and that on the heavily loaded section lowered. There is a slight difference in phase between the two bus-bars, but the voltage of the bars can be equal to each other. The voltage regulation from each bus-bar is therefore unaffected.

Considering the case when two bus-bar sections A_1 and A_2 are each supplied by a 30,000 kVA. 3-phase alternator and connected through a 30,000 kVA. 40 per cent. reactor. The load on section A_1 feeders is 15,000 kVA. and that on section A_2 feeders 45,000 kVA. The bus-bar voltage is 11,000 volts and the load power factor is the same in each case. Determine (1) the voltage drop across the reactor if the two sets are equally loaded; (2) the angle by which the phase of the voltage on section A_1 must be advanced so that the alternators are equally loaded.

When sets are equally loaded the power transferred = 15,000 kVA.

Neglecting resistance drop the voltage drop across reactor

$$= E_N \times \frac{X}{100} \text{ volts}$$

$$= \frac{11{,}000}{\sqrt{3}} \times \frac{15{,}000}{30{,}000} \times \frac{40}{100}$$

$$= 1{,}270 \text{ volts.}$$

or as loading is 50 per cent. and reactance 40 per cent., volt drop

$$= \frac{E_N}{5} = 1{,}270 \text{ volts.}$$

This is represented by OC, Fig. 420 (*g*).

The voltage vector of alternator A_1 must be advanced by α to produce the reactance voltage OC, and since the triangles CE_1O and E_2OE_1 are equal and $OE_2 = OE_1$, a perpendicular OM will bisect E_1E_2 at right angles and

$$\sin\frac{\alpha}{2} = \frac{ME_2}{E_2O} = \frac{1{,}270}{2} \times \frac{\sqrt{3}}{11{,}000}.$$

$$= 0{\cdot}1 \quad \therefore \alpha = 2 \times 6^\circ$$

$$= 12^\circ.$$

Methods of Connecting Reactors. There are two methods of connecting reactors, apart from the usual single reactor between bus-bar sections : (1) star connection ; (2) ring connection. Some of the features of each are given. Figs. 421 to 423 show main connections.

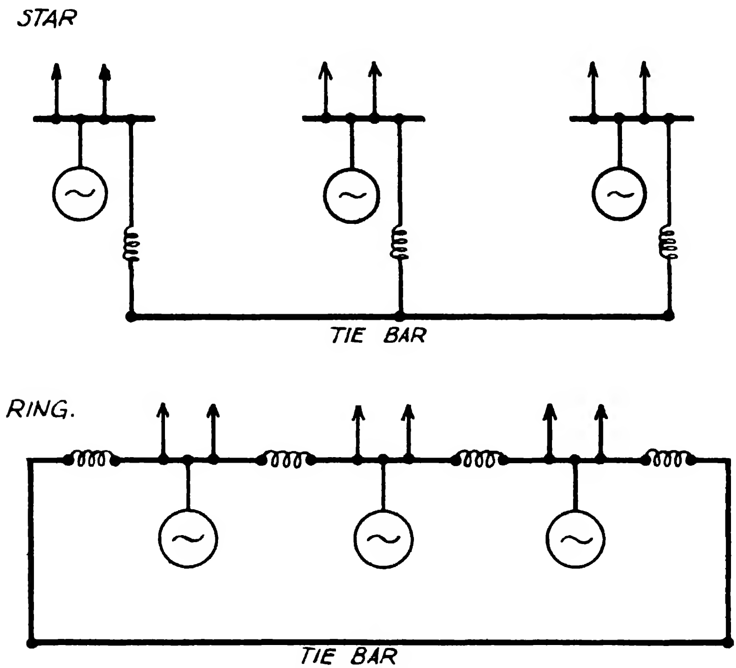


FIG. 421. Bus-bar Sectioning through Reactors.

Star Connection.

(*a*) All bus-bar sections are connected through reactors to a common star point.

(*b*) Any section can be paralleled with any other section through the tie bar so that the formation is not broken if one section is out of service.

(*c*) If the feeders and alternators are suitably proportioned no current need pass through the reactors.

(*d*) Since there are two reactors between each section the individual ohmic value will be reduced compared with that in the ring formation.

(*e*) An additional bus-bar or tie bar is required.

(*f*) The individual sections are connected together *viâ* two reactors in series and a tie bar.

The use of tie bus-bar reactors shows considerable economies

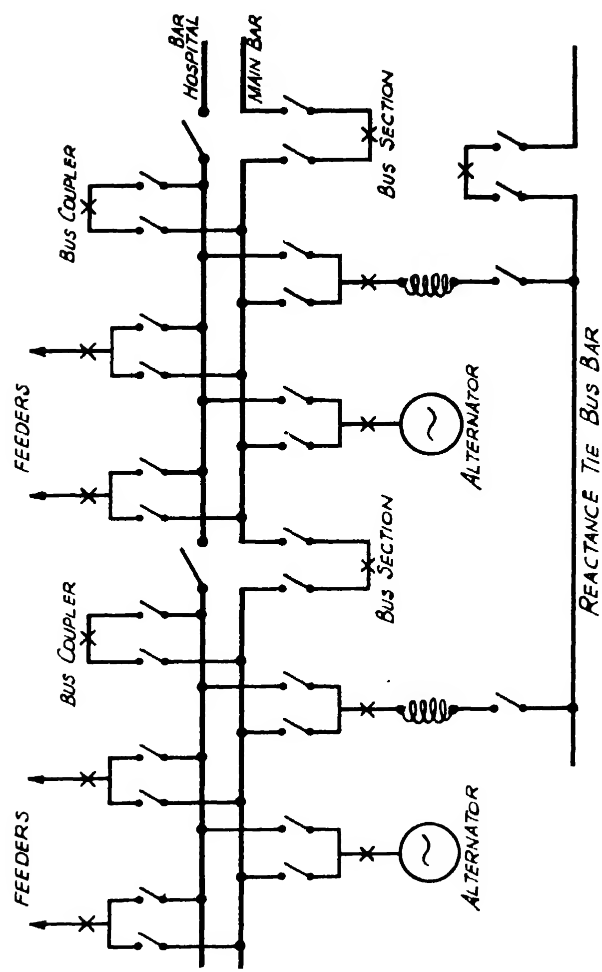


FIG. 422. Diagram of Connections of Tie Bar Reactors.

for under normal conditions little, if any, load will flow through the tie bus-bar and therefore the reactor losses will be negligible and voltage regulation will not be affected. In the event of a transformer or alternator fault, however, the fault current between bus-bar sections must pass through two reactors in series and by this

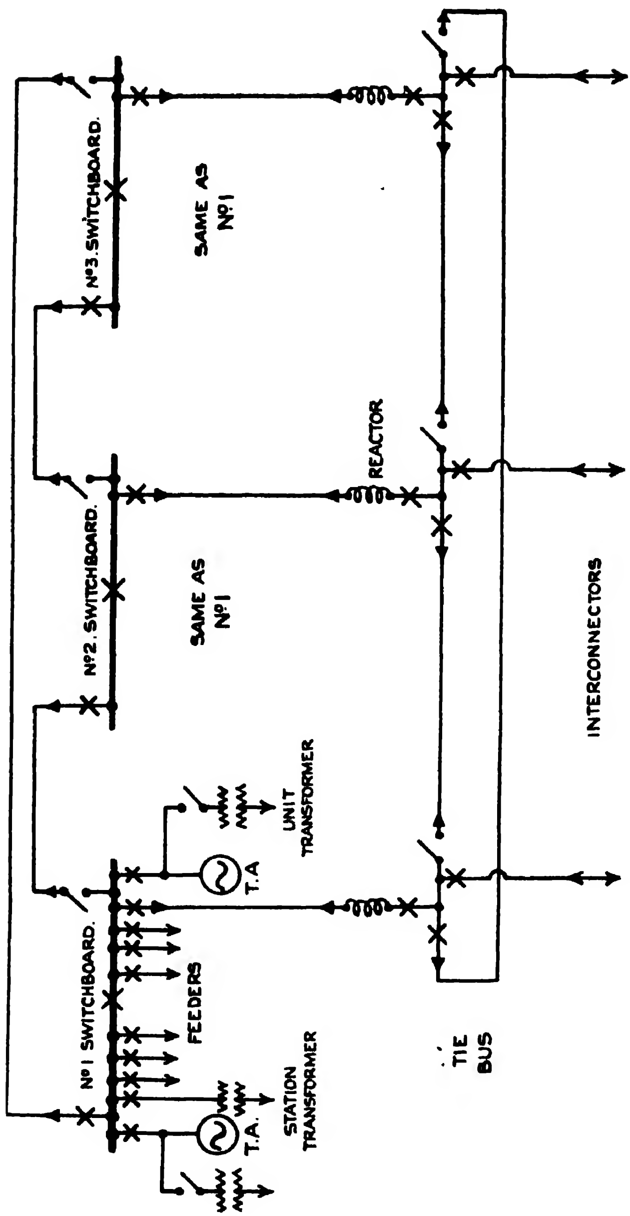


FIG. 423. Diagram of Connections of Tie Bar Reactors.

means the rupturing capacity of the switchgear can be reduced. With transformer and alternator layouts this arrangement can include any number of bus-bar sections connected together and the standby plant capacity can be considerably reduced to suit the requirements of loading. In practice the number of bus-bar sections will be limited by the cost of switchgear and reactors but in general economical arrangements can be designed and reliability of supply is assured with considerable savings in switchgear and transformer costs.

Ring Connection.

(*a*) Reactors are connected alternately in series to form a complete ring.

(*b*) If one section is out of service the formation is broken and there will be considerable reactance between remote sections resulting in poor voltage regulation.

(*c*) Like the star formation, an additional bus-bar is required unless the number of sections and the layout is such that a special bar would be unnecessary.

Group Feeders. To keep the number and sizes of feeder circuit breakers within economical limits it is sometimes necessary to group a number of works auxiliary feeders on separate boards and use a more convenient size of circuit breaker. These auxiliary switchboards are connected to the main boards by way of reactors and only one higher rupturing capacity circuit breaker is necessitated per group of works feeders. The number of works feeders in any group will depend primarily on the current loading and the degree of separation required on the outgoing side of the reactor. To avoid difficulties with voltage regulation it is usually advisable to limit the value of such a group feeder reactance to about 7 per cent. *i.e.*, when the full load current passes through it the drop is 7 per cent. of the main bus-bar volts. In order to send current through the group reactor the main bus-bar must be somewhat higher in voltage by an amount depending on the power factor of the load.

Reactor Rating. Two methods are in use, (1) The " Percentage Reactance and Resistance Method " and (2) ohmic values of reactance and resistance. Voltage transformations, however, introduce certain complications and both of these methods are outlined. Since resistance does not appreciably affect the result it is usually neglected.

The following examples will serve to illustrate the general method of estimating the reactor rating, etc. :—

$$\text{Load to be transferred} = 5{,}000 \text{ kVA.}$$

$$\text{Rupturing capacity of switchgear} = 150 \text{ MVA.}$$

$$\text{Working voltage} = 11{,}400 \text{ volts.}$$

$$\text{Full load current } I_{FL} = \frac{5{,}000 \times 1{,}000}{\sqrt{3} \times 11{,}400}$$

$$= 253 \text{ amps.}$$

$$\text{Fault current } I_{sc} = \frac{150{,}000 \times 1{,}000}{\sqrt{3} \times 11{,}400}$$

$$= 7{,}600 \text{ amps.}$$

$$\text{Reactance per phase } X = \frac{E_N}{I_{sc}} = \frac{11{,}400}{\sqrt{3} \times 7{,}600}$$

$$= 0{\cdot}87 \text{ ohm.}$$

In practice it is usual to keep within the assigned rupturing capacity of the switchgear and in this case we will assume 100 MVA. to be the extreme limit (allows for equivalent reactance on incoming side).

$$\text{Then } I_{sc} = \frac{100{,}000 \times 1{,}000}{\sqrt{3} \times 11{,}400} = 5{,}060 \text{ amps}$$

$$X \text{ per phase} = \frac{11{,}400}{\sqrt{3} \times 5{,}060} = 1{\cdot}3 \text{ ohms.}$$

$$I\,X \text{ drop} = 253 \times 1{\cdot}3$$

$$= 330 \text{ volts.}$$

$$\text{Reactance } X \text{ per cent.} = \frac{330 \times \sqrt{3}}{11{,}400} \times 100$$

$$= 5 \text{ per cent.}$$

$$\text{kVA. rating} = \frac{I^2_{FL} \times X}{1{,}000} \text{ single-phase.}$$

$$= \frac{I^2_{FL} \times X}{1{,}000} \times 3 \text{ three-phase.}$$

$$= \frac{253^2 \times 1{\cdot}3 \times 3}{1{,}000}$$

$$= 250 \text{ kVA.}$$

$$\text{or kV.Ar. rating} = 5 \text{ per cent.} \times 5{,}000 \text{ kVA.}$$

$$= 250 \text{ kVAr.}$$

Fig. 424 shows a typical diagram of connections for a large station employing reactors between two sets of bus-bars.

The data pertaining to this layout are as follows :—

Alternators

Output	= 60 MW., M.C.R. 0·8 power factor.
Reactance	= 15 per cent.
Voltage	= 14 kV.

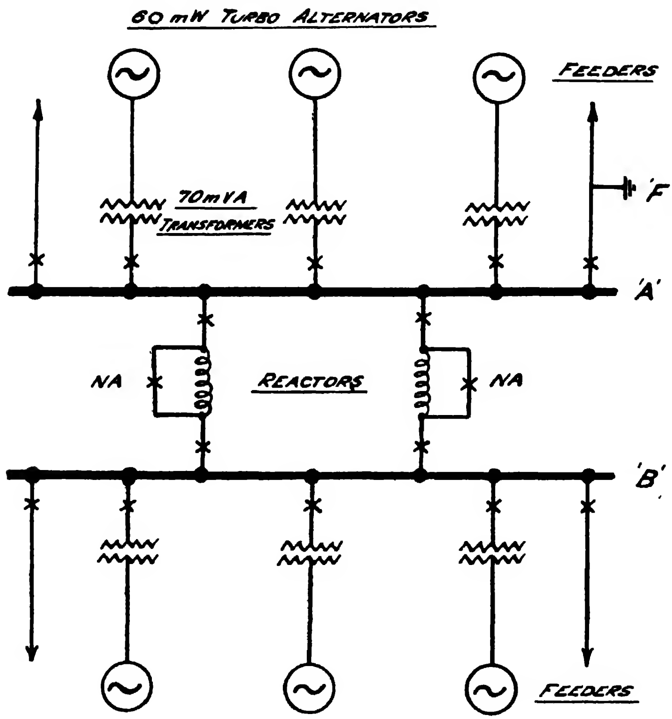


FIG. 424.

Transformers

Output	= 70 MVA.
Reactance	= 10 per cent.
Ratio	= 66/14 kV.

Switchgear

Guaranteed rupturing capacity	= 1,500 MVA
Voltage	= 66 kV.

Single-phase reactors of the iron-core oil-immersed metal-clad type are to be used working at a voltage of 66 kV.

Alternators

$$\text{MVA} = \frac{60}{0\cdot 8} = 75.$$

Transformers 70 MVA = 10 per cent. reactance,

$$\text{or } \frac{75}{70} \times 10 = 10\cdot 7 \text{ per cent. at 75 MVA.}$$

On each bus-bar there is $15 + 10\cdot 7 = 25\cdot 7$ per cent. on 75 MVA $\times$ 3 or 25·7 per cent. reactance on 225 MVA.

$$= 225 \times \frac{100}{25\cdot 7} = 875 \text{ MVA.}$$

This is the power behind fault "F" from "A" bus-bar. A similar amount of power can be fed from "B" bus-bar. The MVA breaking capacity of the switchgear is 1,500, therefore the amount that can be safely transferred is given by

$$1{,}500 - 875 = 625 \text{ MVA.}$$

The fault MVA that can be fed from "B" bus-bar, *i.e.*, 875, must be limited to 625.

Let the percentage total plant reactance on "B" bus-bar, including reactors, be "Bx" per cent,

then $$625 = \frac{75 \times 3 \times 100}{Bx}$$

$\therefore$ $$Bx = \frac{22{,}500}{625} = 36 \text{ per cent.}$$

Since the combined alternator and transformer reactances based on 3×75 MVA = 25·7 per cent., the reactors to be used should have a value of $36 - 25\cdot 7 = 10\cdot 3$ per cent. based upon 225 MVA,

or based on 75 MVA $= \dfrac{10\cdot 3}{3} = \underline{\underline{3\cdot 44 \text{ per cent.}}}$

If we assumed both reactors to be in circuit together, the value for each would be $3\cdot 44 \times 2 = 6\cdot 88$ per cent., thus making a combined equivalent value of 3·44, *i.e.*,

$$\frac{1}{X_E} = \frac{1}{X_B} + \frac{1}{X_B} \text{ or } \frac{1}{6\cdot 88} + \frac{1}{6\cdot 88}$$

from which $$X_E = 3\cdot 44 \text{ per cent.}$$

Let $\overline{X}$ per cent. = reactance volts drop at " M " MVA.

$$M = \frac{\sqrt{3} \,.\, E \,.\, I_{FL}}{10^6} \qquad \therefore\ I_{FL} = \frac{M\ 10^6}{\sqrt{3} \,.\, E.}$$

Let $\underline{X}$ = reactance in ohms.

$$\text{then } \overline{X} \text{ per cent.} = \frac{\sqrt{3}\, I_{FL}\, \underline{X}\ 100}{E}$$

Substituting for I_{FL} we get

$$\overline{X} \text{ per cent.} = \frac{\sqrt{3}\, \underline{X}\ 100\, M \times 10^6}{\sqrt{3}\, E^2}$$

$$\text{or } \underline{X} = \frac{E^2\, \overline{X} \text{ per cent.}}{M \times 10^8} \text{ ohms.}$$

Now, considering possible load transference and assuming that one of " A " bus-bar machines to be undergoing maintenance, it may be necessary to transfer the load on one machine from " B " to " A," *i.e.*, 75 MVA.

Assuming one reactor to be in circuit, then the required reactance will be given by :—

$$\underline{X} = \frac{66{,}000 \times 66{,}000 \times 3{\cdot}44}{75 \times 10^8}$$

$$= \underline{\underline{2 \text{ ohms per phase.}}}$$

The kVA rating of reactor (single-phase) $= \dfrac{I^2_{FL} \times X}{1{,}000}$.

We assumed that a load equivalent to one machine would be transferred, *i.e.*, 75 MVA.

$$\therefore \qquad I_{FL} = \frac{75 \times 10^6}{\sqrt{3} \times 66{,}000} = 656 \text{ amps.}$$

$$\text{Rating of reactor at this current} = \frac{656^2 \times 2}{1{,}000}$$

$$= \underline{\underline{860 \text{ kVA.}}}$$

The **3-phase** group $= \underline{\underline{2{,}580 \text{ kVA.}}}$

This working may be checked as follows :—

I_{sc} = short-circuit current.
I_{FL} = full-load current.
X = reactance in ohms per phase.

Then $$I_{sc} = \frac{E}{\sqrt{3}\,X.}$$

$$\text{Reactance X per cent.} = \frac{\sqrt{3}\,I_{FL}\,X\,100}{E}$$

$$\therefore \quad \frac{100}{\text{X per cent.}} = \frac{E}{\sqrt{3}\,I_{FL}\quad X} = \frac{\sqrt{3}\,I_{sc}\,X}{\sqrt{3}\,I_{FL}\,X} = \frac{I_{sc}}{I_{FI}}$$

Alternators. 75 MVA, 15 per cent. reactance, 14 kV.

$$\text{Voltage to neutral} = \frac{14{,}000}{\sqrt{3}}$$

$$\text{Full load current } I_{FL.} = \frac{75{,}000 \times 1{,}000}{14{,}000 \times \sqrt{3}}$$

$$= \frac{75{,}000}{14 \times \sqrt{3}}$$

$$\text{Full load drop} = I_{FL} \times X.$$

$$= \frac{75{,}000}{14 \times \sqrt{3}}\,X.$$

Also $$\frac{75{,}000}{14 \times \sqrt{3}} \times X = \frac{15}{100} \times \frac{14{,}000}{\sqrt{3}}$$

hence $$X = \frac{15}{100} \times \frac{14{,}000}{\sqrt{3}} \times \frac{14 \times \sqrt{3}}{75{,}000}$$

$$= 0{\cdot}392 \text{ ohm.}$$

Expressed in an equivalent reactance in the 66 kV. side, its value then becomes :—

$$\frac{X}{\left(\frac{E}{E_1}\right)^2} = \frac{0{\cdot}392}{\left(\frac{14}{66}\right)^2} = 8{\cdot}74 \text{ ohms., } X_1.$$

Transformers : 70 MVA. 10 per cent. reactance, ratio 14/66 kV.

$$I_{FL} = \frac{70 \times 10^6}{14{,}000 \times \sqrt{3}} = \frac{70{,}000}{14 \times \sqrt{3}}$$

$$\text{Full load drop} = \frac{70{,}000}{14 \times \sqrt{3}} \times X = \frac{10}{100} \times \frac{14{,}000}{\sqrt{3}}$$

$$X = \frac{1}{10} \times \frac{14{,}000}{\sqrt{3}} \times \frac{14 \times \sqrt{3}}{70{,}000}$$

$$= 0{\cdot}28 \text{ ohm.}$$

Expressed as an equivalent reactance in the 66 kV. side, its value then becomes :—

$$\frac{0\cdot28}{\left(\frac{14}{66}\right)^2} = 6\cdot24 \text{ ohms.}$$

Total reactance in each circuit (A, B, and C; D, E and F, Fig. 425).

$X_T = 8\cdot74 + 6\cdot24 = 14\cdot98$ ohms per phase.

$$\text{Fault current } I_{sc} = \frac{\text{Voltage (line to neutral)}}{\text{Total reactance per phase}}$$

$$= \frac{66{,}000}{14\cdot98 \times \sqrt{3}} \text{ amps.}$$

$$\text{Fault MVA (three machines)} = \frac{66{,}000}{14\cdot98 \times \sqrt{3}} \times \frac{\sqrt{3} \times 66{,}000}{10^6}$$

$$= \underline{\underline{875}} \text{ as before.}$$

$$1{,}500 - 875 = 625 \text{ MVA.}$$

This is the limiting value of the fault MVA from bus-bar " B " the corresponding fault current $I_{sc} = \dfrac{625 \times 10^6}{66{,}000 \times \sqrt{3}}$.

$$\text{Also fault current } I_{sc} = \frac{E}{\sqrt{3}X} = \frac{625 \times 10^6}{66{,}000 \times \sqrt{3}}$$

$$\therefore \qquad \text{reactance } X = \frac{66{,}000^2 \times \sqrt{3}}{\sqrt{3} \times 625 \times 10^6}$$

$$= 7 \text{ ohms.}$$

$$(R_1 + X_{TDEF}) \text{ or } (R_2 + X_{TDEF}) = 7 \text{ ohms.}$$

Assuming as before to have only one reactor in use, then the equivalent reactance circuit, Fig 425 will hold.

$$\text{Equivalent} \qquad X_{TDEF} = \frac{14\cdot98}{3} = 5 \text{ ohms.}$$

$$R_1 = R_2 = (7 - 5) = \underline{\underline{2 \text{ ohms}}} \text{ as before.}$$

The total fault MVA from either of bus-bar " A " or " B " could also be estimated as follows :—

Alternator	15	per cent.
Transformer $\frac{75}{70} \times 10$	10·7	,, ,,
	25·7	,, ,,

$$\frac{I_{sc}}{I_{FL}} = \frac{100}{25 \cdot 7}$$

$$\therefore \qquad I_{sc} = \frac{100}{25 \cdot 7} \times \frac{75 \cdot 10^6}{\sqrt{3} \times 66{,}000}$$

$= 2{,}560$ amps. per machine.

$$\text{Total fault MVA} = \frac{\sqrt{3} \times 2{,}560 \times 66{,}000 \times 3}{10^6}$$

$= \underline{875}$ as before.

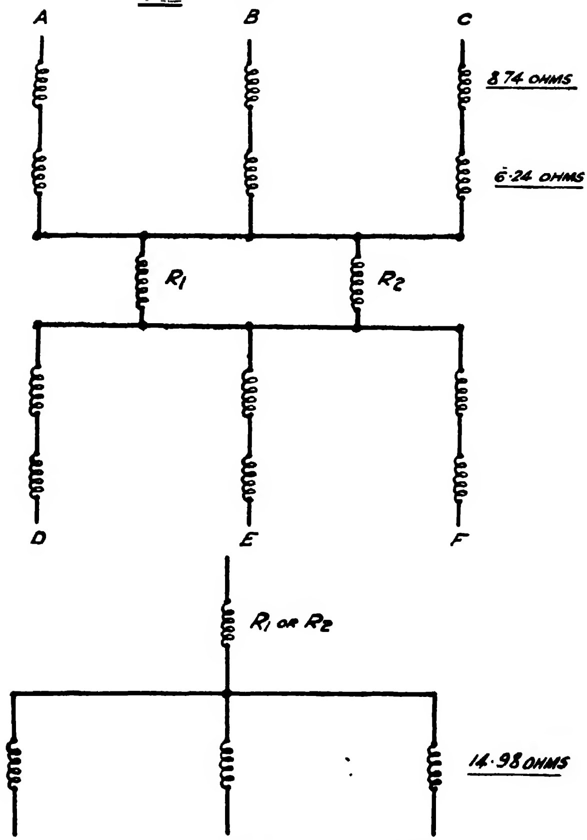


FIG. 425. Bus-bar Layout with Reactors.

$$\text{X per cent.} = \frac{\sqrt{3} \times I_{FL} \times X \times 100}{E} = \frac{\sqrt{3} \times 656 \times 2 \times 100}{66{,}000} =$$

3·44 per cent. on 75 MVA.

It will be observed that the calculations provide for working up to the guaranteed rupturing capacity of the switchgear whereas in practice a reasonable margin would in general be allowed for.

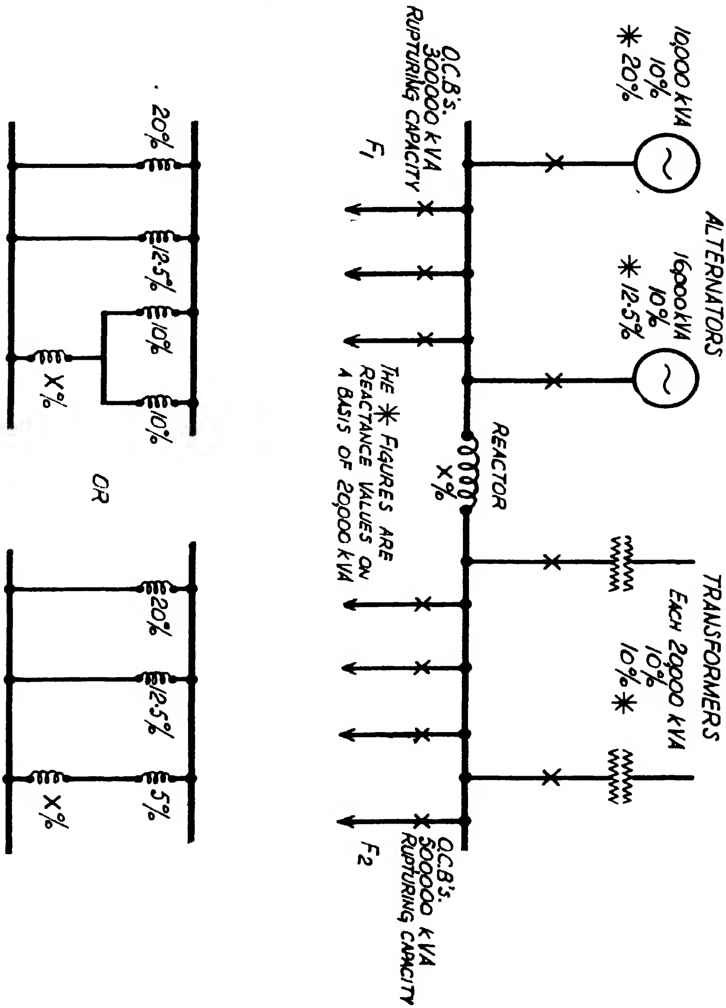


FIG. 426.

Many of the auxiliary services in a station are supplied *viâ* a transformer, and it is necessary to keep the fault conditions within

certain limits. For example, a 1,000-kVA. transformer gives supply to a 400 volt, 25 MVA switchboard, and the conditions are as follows :—

Fault MVA on high voltage side of transformer = 75.
This is 7·5 MVA at 10 per cent.

Transformer reactance = 6·00 per cent.

7,500 kVA. at 10 per cent. based on 1,000 kVA.

$$\frac{1{,}000}{7{,}500} \times 10 \text{ per cent.} = 1{\cdot}33 \text{ ,, ,,}$$

Total = 7·33 ,, ,,

$\therefore$ Fault kVA. on low voltage side of transformer $= \dfrac{1{,}000}{7{\cdot}33} \times 100$
$= 14{,}000$ approx.

Considering example shown in Fig. 426. It is assumed that the worst condition is a symmetrical three-phase short circuit on one of the feeders (F_1).

Alternators alone :

$$\text{Resultant reactance} = \frac{1}{\dfrac{1}{20} + \dfrac{1}{12{\cdot}5}} = \frac{1}{0{\cdot}05 + 0{\cdot}08} = 7 \text{ per cent.}$$

$$\text{Short circuit kVA.} = \frac{100}{7{\cdot}7} \times 20{,}000 = 260{,}000 \text{ kVA.}$$

Transformers alone (without reactor) :

$$\text{Resultant reactance} = \frac{1}{\dfrac{1}{10} + \dfrac{1}{10}} = \frac{1}{0{\cdot}10 + 0{\cdot}10} = 5 \text{ per cent.}$$

$$\text{Short-circuit kVA.} = \frac{100}{5} \times 20{,}000 = 400{,}000 \text{ kVA.}$$

Alternators and transformers together (without reactor) :

$$\text{Resultant reactance} = \frac{1}{\dfrac{1}{7{\cdot}7} + \dfrac{1}{5}} = \frac{1}{0{\cdot}13 + 0{\cdot}2} = 3{\cdot}04 \text{ per cent.}$$

$$\text{Short circuit kVA.} = \frac{100}{3{\cdot}04} \times 20{,}000 = \underline{660{,}000 \text{ kVA.}}$$

To limit the short circuit kVA. to 300,000 kVA. the total resultant reactance must not exceed

$$\frac{100}{300{,}000} \times 20{,}000 = 6 \cdot 66 \text{ per cent.}$$

The value of reactance required in the reactor (X) may be calculated as follows :—

$$\frac{1}{7 \cdot 7} + \frac{1}{5 + X} = \frac{1}{6 \cdot 66}$$

$$\therefore \frac{1}{5 + X} = \frac{1}{6 \cdot 66} - \frac{1}{7 \cdot 7}$$

$$\frac{1}{5 + X} = \frac{1}{50}$$

$$5 + X = 50 \quad \therefore X = 45 \text{ per cent.}$$

Check calculation :

$$\text{Total resultant reactance} = \frac{1}{\frac{1}{7 \cdot 7} + \frac{1}{5 + 45}} = \frac{1}{0 \cdot 13 + 0 \cdot 02}$$

$$= 6 \cdot 66 \text{ per cent.}$$

$$\text{Short circuit kVA.} = \frac{100}{6 \cdot 66} \times 20{,}000.$$

$$= 300{,}000 \text{ kVA.}$$

The proportions of this total short circuit kVA. supplied from the two sources are :—

$$\text{Alternators } \frac{100}{7 \cdot 7} \times 20{,}000 = 260{,}000 \text{ kVA.}$$

$$\text{Transformers } \frac{100}{5 + 45} \times 20{,}000 = 40{,}000 \text{ kVA.}$$

$$\text{Total} = 300{,}000 \text{ kVA.}$$

In these calculations it is assumed that the equivalent reactance of the incoming supply to the transformers may be neglected. The method of allowing for this is shown in the previous example.

It is required to give a supply of 15,000 kVA. from the two transformers and consequently the reactor must be designed for a continuous current rating corresponding to 15,000 kVA. and a reactance of $45 \times \frac{15{,}000}{20{,}000} = 33 \cdot 8$ per cent. and under short circuit

conditions it must be capable of carrying 50,000 kVA. approx. for a period determined by the setting of the circuit breakers, say 5 seconds. (Considering fault on feeders F2, the short circuit kVA. due to the alternators *viâ* the reactor is $\frac{100}{7{\cdot}7 + 33{\cdot}8} \times 20{,}000 = 48{,}400$, say 50,000 kVA.)

The system is three-phase, 6,600 volts. The characteristics of the reactor would be as follows :—

$$\text{Continuous current rating} = \frac{15{,}000 \times 1{,}000}{6{,}600 \times \sqrt{3}} = 1{,}310 \text{ amps.}$$

$$\text{Reactance voltage per phase} = 33{\cdot}8 \text{ per cent.} \times \frac{6{,}600}{\sqrt{3}} = 1{,}280 \text{ volts.}$$

$$\text{Equivalent capacity} = 33{\cdot}8 \text{ per cent.} \times 15{,}000 = 5{,}070 \text{ kVA.}$$

$$\text{or } \frac{1{,}310 \times 1{,}285 \times 3}{1{,}000} = 5{,}070 \text{ kVA.}$$

$$\text{Reactance per phase} = \frac{1{,}280}{1{,}310} = 0{\cdot}98 \text{ ohm.}$$

$$\text{Short circuit current} = \frac{50{,}000 \times 1{,}000}{6{,}600 \times \sqrt{3}} = 4{,}400 \text{ amps.}$$

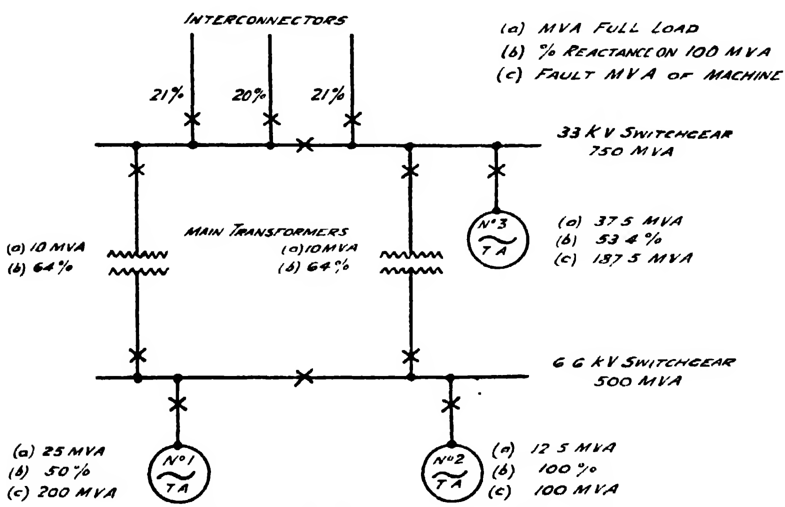


FIG. 427. Typical Station Reactance Diagram.

Fig. 427 shows a typical station reactance diagram.

CHAPTER XIV

SWITCHGEAR

Importance of Switchgear. Of the many elements which enter into power station design, switchgear is one of the most important, for serious failure may cause complete crippling of the station. Great care must be taken in its selection so as to ensure high reliability under all conditions of service. Switchgear, whether for main or auxiliary services is a vital link in the insurance of reliability of supply. The functions of switchgear may be briefly summarised as follows :—

(1) To localise the effects of faults by operation of protective equipment and so automatically disconnect faulty plant from the system.

(2) To break efficiently short circuits without giving rise to dangerous conditions.

(3) To facilitate re-distribution of loads, inspection and maintenance on the system.

The design and construction of the switchgear layout should be such that a reliable service is obtained under all operating conditions and in as direct a route as possible from the alternators to the outgoing feeders. The choice of suitable switchgear is more or less governed by the maximum short-circuit MVA it is called upon to deal with and also to some degree upon its relation to the system of which it forms a part. The exact value of the rupturing capacity of the main switchgear is usually rather difficult to determine because of the complicated nature of many of the systems. It is necessary to obtain some idea of the magnitude so that suitable circuit-breakers can be installed and the worst possible condition will govern their selection.

The magnitude of fault current depends on many factors which may vary from hour to hour on a system. Probably the two extreme conditions would be—a severe short-circuit at times of heavy load and lagging power factor and a mild short-circuit during times of light load and leading power factor.

The former would be the worst condition, whilst the latter gives the smallest short-circuit current, since the alternators are under-excited with a corresponding reduction in terminal voltage.

Circuit breakers with the highest voltage ratings should possess the following characteristics :

(*a*) They should be capable of interrupting inductive and capacitive circuits and fault currents of all values within their rating.
(*b*) They should make the interruption at the first "current zero" after contact separation, without risk of restriking, without producing over-voltages in the electrical system and without temporary or permanent deterioration of the insulation or interrupting ability.
(*c*) The opening time, i.e., the time interval between receipt of tripping impulse and contact separation should be the minimum mechanically possible.
(*d*) Electrically and mechanically they should have high reliability.

Systematic and simple design and proper subdivision of switchgear is the surest method of obtaining reliability of supply without entailing undue expense, not only in the first installation but more so as the station grows. Oil-immersed circuit-breakers were favoured in the past, but air blast-breakers are now being widely used and appear to be giving satisfactory service. The rapid increases in demand for energy and the necessity for taking every precaution to ensure continuity of supply has made it essential to carry out reorganisation of many of the existing power station switchboards. Rupturing capacities for various types of switchgear and voltages are given in Table 58.

The principal ratings at the present time for high voltage working are as follows :—

275 kV	5,500 MVA
132 ,, ...	3,500 ,,
66 ,, ...	2,500 ,,
33 ,, ...	1,500 ,,
11 ,, ...	500 ,,
6·6 ,, ...	350 ,,

These are the upper rated rupturing capacities suggested.

Layout and Systems of Connections. When designing a new station the first step is to prepare a single-line diagram of main connections. This diagram should show the bus-bar arrangements, circuit-breakers, alternators, transformers, and reactors and may be gradually added to throughout the development of the design-stages to include all protective apparatus and instruments.

The next point of importance is the arrangement of the switchgear. This will be governed by a number of factors, probably the most important of which are reliability, flexibility, space, safety, simplicity and cost. Other factors having a direct bearing on the

layout are capacity of station, method of control, number of alternators and feeders and the system of connections adopted.

The usual practice is to house the main switchgear in a separate building or buildings in the case of a large station whilst the auxiliary switchgear can be grouped into units or boards and placed as near as possible to the auxiliaries which it controls.

An electrical annexe in the form of an intermediate floor between the turbine house floor level and basement, extending the full length of the turbine house, may be provided for this purpose. This arrangement has been adopted in some stations and has proved very useful and convenient, as the majority of the auxiliary switchgear can be accommodated on this floor. This enables the opposite side of the turbine house to be kept entirely apart for the use of mechanical auxiliaries, etc. In some cases, however, the more important switchgear for controlling the chief circuits to the auxiliaries is placed in a house adjoining the main switchgear. The switchgear controlling the more important auxiliary transformers, house-sets and inter-connecting circuits may be arranged for electrical operation from the control room or alternatively from a sub-control room.

There are several advantages in placing the main switchgear in an entirely separate building; no interference from the turbine house in the case of burst steam mains or other causes, less noise, reduced fire risk, better facilities for exit of the large number of feeder cables, and extensions can be more easily carried out at a later date if necessary. The switchgear should be placed as close as possible to the generating plant, and in most cases a suitable layout would be obtained by having the switch houses adjoining and parallel to the longitudinal axis of the turbine house. This layout brings about a considerable saving in cabling and reduces the cost of land and building. If desired the feeder switchgear could be placed in a separate building away from the main buildings. This would be justifiable in a large station although more expense would be entailed.

The arrangement of switchgear and buildings should be such that the principles already outlined are strictly adhered to. There are many ways in which the switchgear may be arranged, some of which are :—

(1) To parallel the alternators and main transformers independently (Fig. 428 (*a*)).

(2) Switch each alternator and transformer as a unit (Fig. 428 (*b*)).

(3) Parallel the alternators and switch each transformer and feeder as a unit (Fig. 428 (c)).

(4) A combination of systems (1) and (3) as Fig. 429.

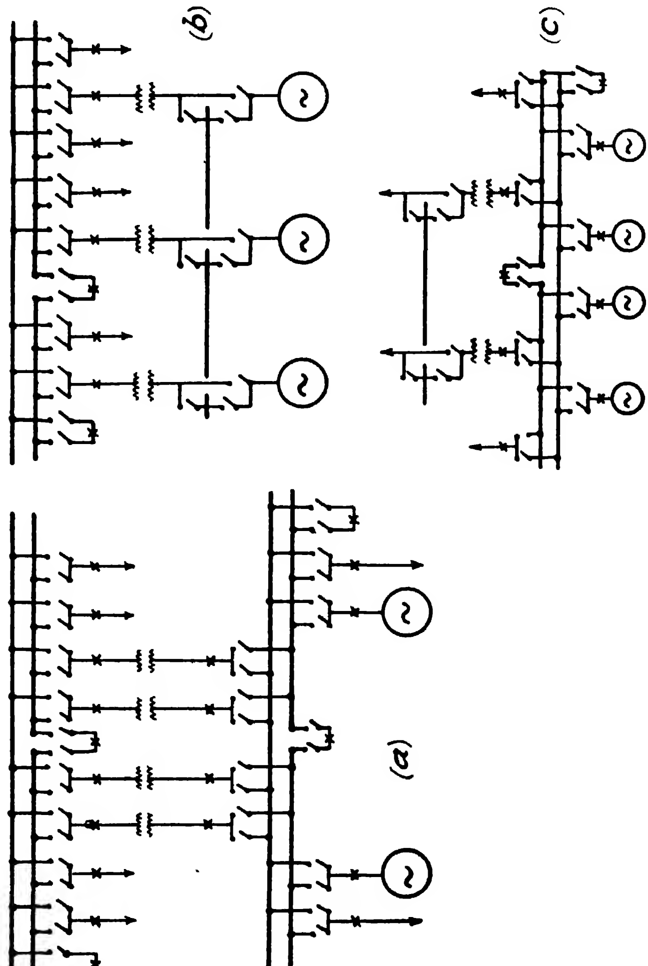


FIG. 428 (a)–(c). Systems of Main Connections.

Some features of these systems are :—

System 1.

(a) It is flexible and makes possible the use of generating plant for feeders at generation voltage.

(b) Only the necessary transformer capacity need be retained in circuit, thus enabling the highest efficiency to be obtained.

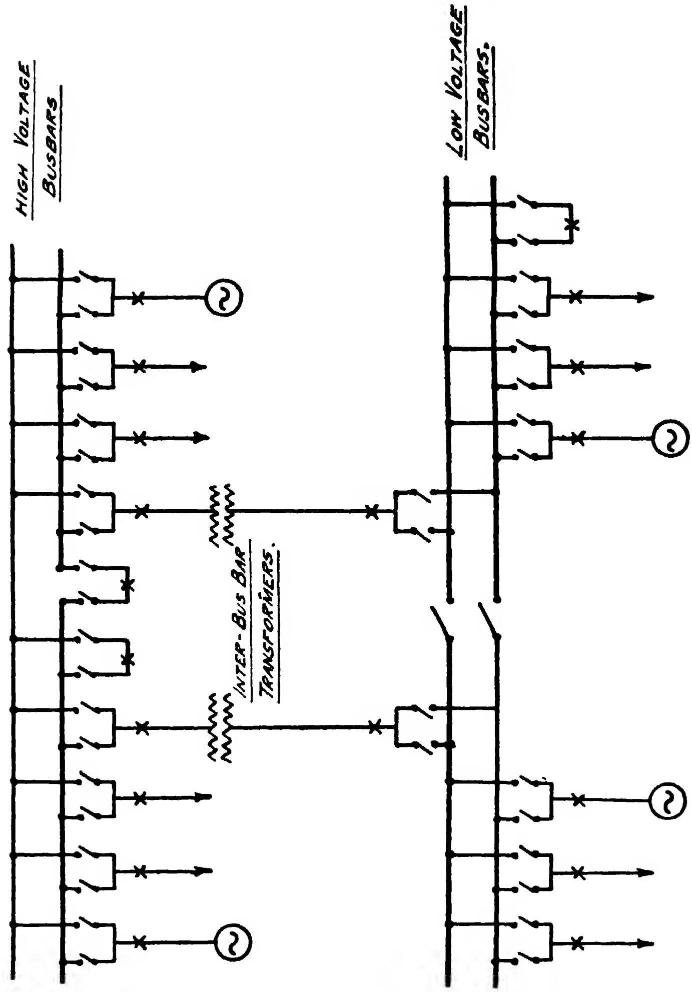


FIG. 429. Systems of Main Connections (*continued*).

(*c*) All transformers may be of the same output, thereby economising in first cost and reducing the spare plant required.

(*d*) In the event of transformer breakdown no other plant need be put out of service. If circuit-breakers are included on both sides of transformers sensitive protective devices may be used.

(*e*) The system is more expensive than (2) and (3), but the cost may be somewhat offset by the saving in transformer capacity.

System 2.

The practice of treating the transformer and alternator as a unit is one which has been frequently adopted in many stations.

(*a*) The main transformer output is the same as its alternator, less an amount required for auxiliary purposes, *i.e.*, the unit transformer.

(*b*) Circuit-breakers are not necessary on the alternator side, although, if desired, a transfer-bus with selector isolating switches may be included. With this arrangement it would be possible to work the alternators with any main transformer.

(*c*) Particularly adaptable where the alternators are few and the high voltage feeders numerous.

(*d*) Reduced rupturing and current capacities of the circuit-breakers.

(*e*) Simplified arrangement of switchgear and cabling.

(*f*) Protection and control as a unit.

(*g*) By running up the alternator connected solidly to its transformer there is no rush of magnetising current.

System 3.

(*a*) This system can be used to advantage where the alternators are many and the local supply is an appreciable proportion of the station output and working at generation voltage.

(*b*) The loading of the feeders may vary to such an extent that the transformers would have to be of different outputs, thus making it difficult to secure economical spare plant.

(*c*) In case of transformer failure the feeder is out of service until repairs are effected.

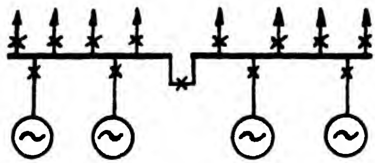
System 4.

With the advent of high-voltage alternators it has been found necessary in existing stations to make provision for stepping down the voltage to that of the switchgear already installed. An inter bus-bar transformer of suitable output can be arranged to deal with this load.

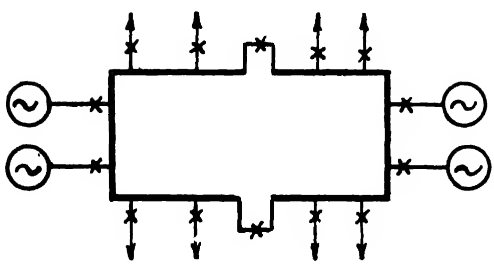
On large turbo-alternators with lower voltages it is possible to use two-circuit breakers with each alternator and so dispose them at the ends of a switchboard that the bus-bar currents are maintained within safe limits. Care is required in designing the cable run and laying the cables so that the impedances of the two lengths of cable are equal, otherwise one circuit breaker will carry considerably more current than the other with the danger of overheating. There is also the possibility that one of the two circuit-breakers might be opened leaving the other to carry the full load of the alternator. This can be guarded against by providing an alarm device when the maximum current is exceeded on either circuit breaker. If each circuit breaker supplies separate switchboards the loading may be arranged accordingly without fear of overloading.

Bus-bar Arrangements. The system sectionalising arrangement should be such that each separated section under fault conditions is supplied from sufficient generating plant and so render it self-

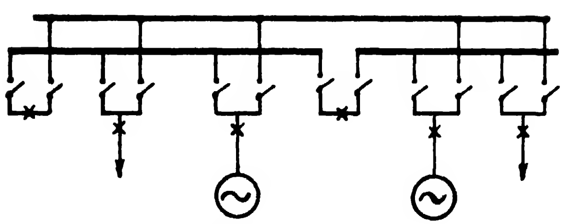
supporting. The synchronising arrangements should also be such that the separate sections of the system can be tied together in as short a time as possible thereby expediting the restoration of possible interrupted supplies. A fault on the main bus-bars is the most serious



SINGLE BUS-BAR



SINGLE RING BUS-BAR



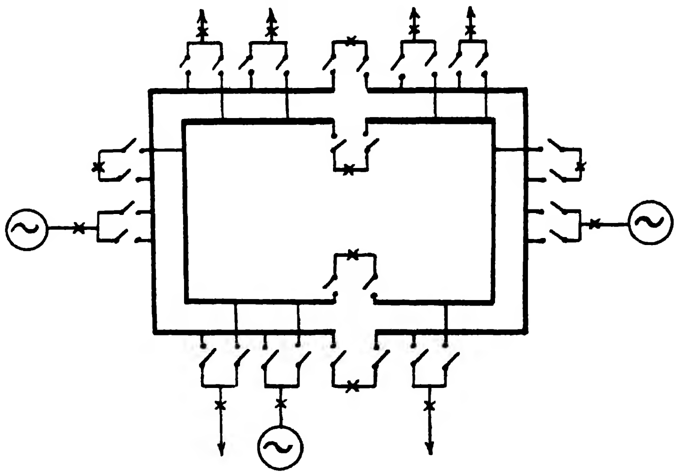
Duplicate Bus-bar.

FIG. 430. Bus-bar Arrangements.

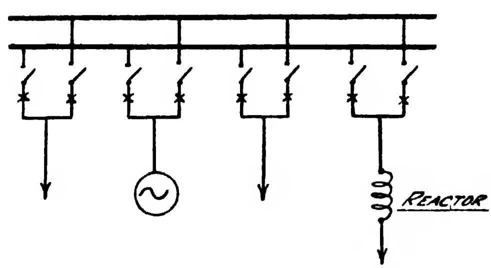
happening that can occur on the electrical side of a power station as the whole of the energy which the alternators connected to such bus-bars are capable of supplying becomes concentrated at the point of fault. Numerous arrangements are in use and Figs. 430 to 433 illustrate a few.

Single Bus-bar. Is seldom used for main switchboards as there

is no stand-by in case of failure of the bus-bars. Work on the bars cannot be undertaken without interrupting the supply. By sectionalising the bars it is possible to secure a reasonable measure of



DUPLICATE RING BUS-BARS.

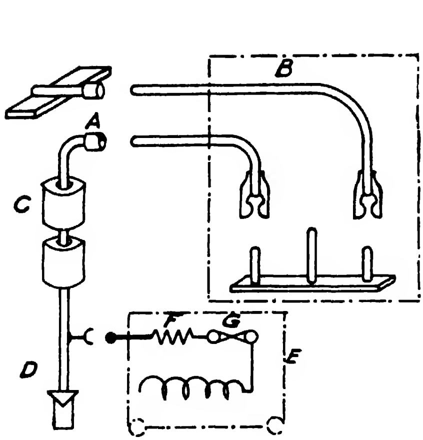


DUPLICATE CIRCUIT-BREAKER LAYOUT

FIG. 431. Bus-bar Arrangements (*continued*).

security in cases of breakdown. It is satisfactory for auxiliary switchboards.

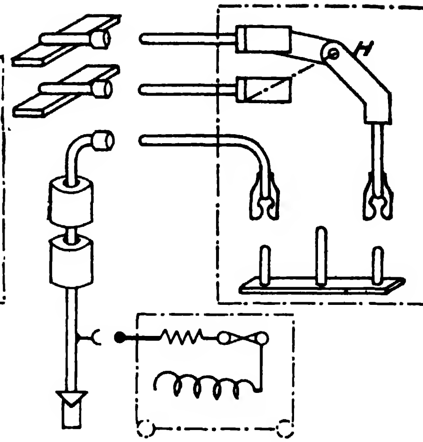
Single Ring Bus-bar. This is an extended form of single bus-bar and makes possible the isolation of any section for modifications or repair. The alternators and feeders on the section affected must be disconnected.



1.

Single Bus.

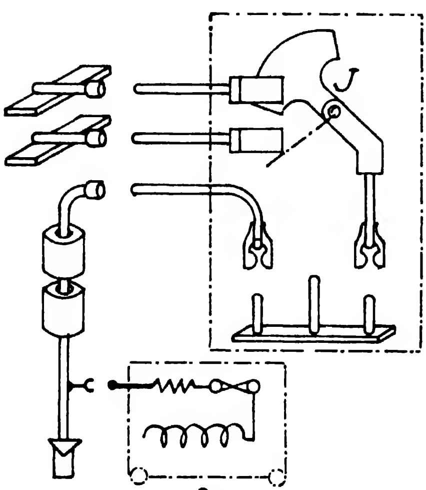
A—Isolating plug and socket.
B—Withdrawable circuit breaker.
C—Current and protective transformers.
D—Feeder cable.
E—Withdrawable voltage transformer.
F—Limiting resistance.
G—High-tension fuse.



2.

Duplicate Bus with Off-load Selector Switch.

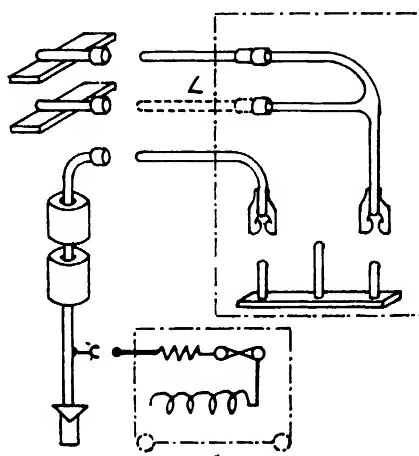
H—Selector switch, off-load change.



3.

Duplicate Bus with On-load Selector Switch.

J—Selector switch, on-load change.



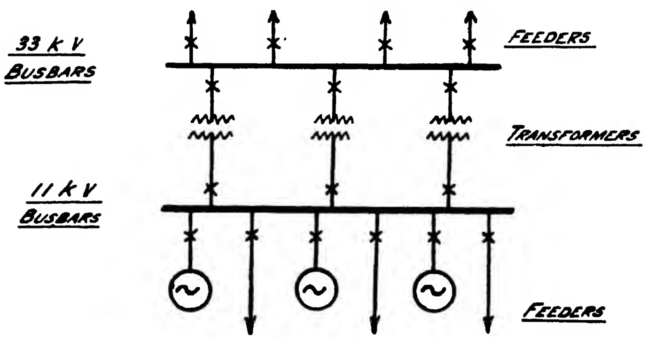
4.

Duplicate Bus with Removable Plugs.

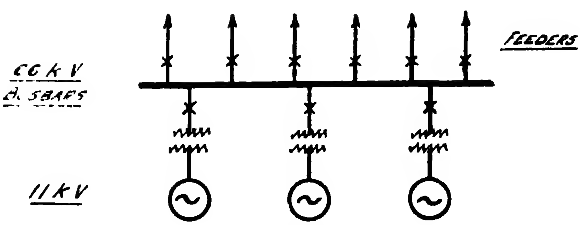
L—Selection plug, off-load.

FIG. 432. Methods of Bus-bar Selection.

Duplicate Bus-bars. To overcome the disadvantages of the single bus-bar systems, duplicate bus-bars are almost universally adopted for all the important switchboards. Duplicate bus-bars provide flexibility in operation and a bus-bar coupler circuit-breaker facilitates linking and provides a spare breaker which can be used in emergency.



(a)



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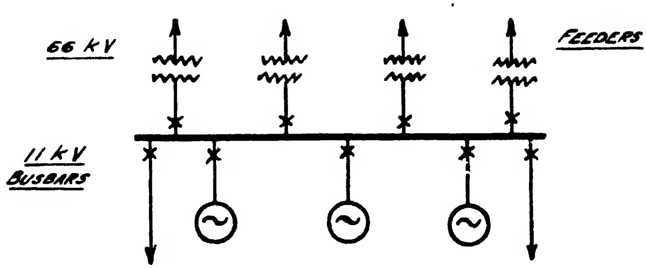

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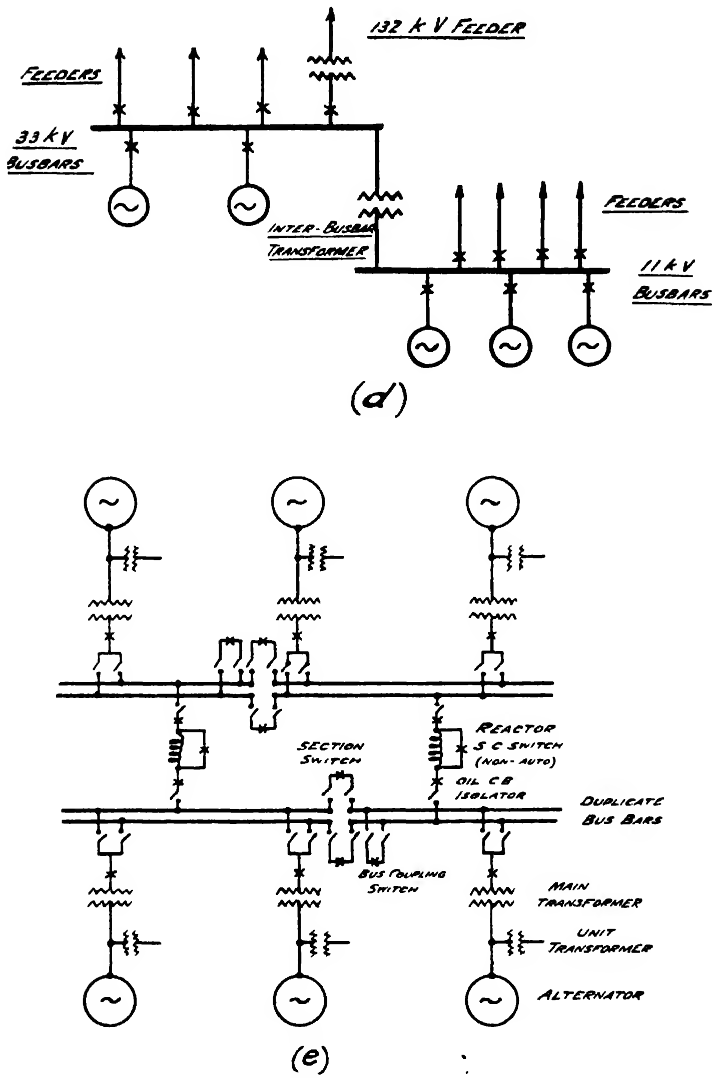


FIG. 433. Bus-bar Arrangements.

The advantages of a spare bus-bar are :—

(1) Cleaning, repairs, modifications and extensions may be undertaken without interruption to the supply.

(2) Feeders may be isolated from the system and worked at different voltages.

(3) Feeders which have undergone repair may be tried out separately by a test set before putting into service.

(4) A supply from an inter-connected station may be received and distributed without running in parallel.

(5) The bus-bars may be used to the best advantage, as non-adjacent sections which are lightly loaded may be paralleled through the spare bar and run as one section.

(6) To take full advantage of this arrangement, provision should be made for synchronising and paralleling the two sets of bus-bars and so enable circuits to be transferred without interruption.

Where control is by single circuit-breaker a separate bus-coupling breaker is required for each section, but if duplicate circuit-breakers are used this coupler can be omitted. The bus-coupler is very useful in the event of failure of closing circuits of alternator or incoming feeder transformer circuit breakers, in which case these breakers may be closed manually on to a spare bus-bar and paralleled through the coupler. With the bus-coupler closed a circuit may be changed over by closing its selector isolating switches on both bus-bars and then opening the isolator on that bus-bar from which the circuit has to be disconnected. This cannot be done with circuit breakers which are isolated by movement of themselves, as with metal-clad gear, and the isolating selector switches must not be interlocked.

The duplicate circuit-breaker arrangement has been adopted on a number of large stations. In a station of, say, 300 MW output, where the switchgear is sub-divided into sections and housed in separate buildings, each section being isolated except for an inter-connector to be used in emergency, then a duplicate circuit-breaker arrangement is justifiable. A point to be borne in mind is that trouble is sometimes experienced due to the fact that interchangeability of circuit-breakers on separated duplicate bus-bar schemes is not as successful as one might expect. Circuit-breakers having "on-load" isolators are sometimes used for the works' feeder circuits and general auxiliary services.

Principles of Layout. The principles to be followed in switchgear layout may be summarised as :—

(1) The design of the individual units should be such that the risks of failure are reduced to a mimimum.

(2) Barriers and partitions should, if possible, separate each unit so that a faulty unit will not interfere with its neighbours. Complete sub-division avoids as far as practicable any serious trouble spreading and damaging the adjoining units or sections.

(3) The layout should be such that any section may be isolated without unduly affecting the service.

(4) To provide easy and safe access for maintenance and general routine inspection.

(5) Where necessary reactors should be used to keep the breaking duty within the capacity of the circuit-breakers.

(6) Provision should be made for handling oil and dealing with fires.

Types of Circuit Breaker. One method of classification divides them into earthed (or dead) tank and live-tank breakers. A further subdivision is single-break and multi-break units. The single-break units may also be of the vertical or horizontal types. On the live tank type, the oil only performs the interrupting or breaking function as the main insulation to earth is provided by insulated supports.

Very high-voltage, high duty circuit breakers require special consideration and the modern air-blast breaker appears to be the most suited having regard to all technical and practical problems to be faced.

Types of Switchgear. The various types of switchgear commonly used are briefly discussed and comparisons made.

Air Break Isolators. Such isolators are used with cellular and similar switchgear, also neutral earthing equipment. They are generally of the off-load type but it is sometimes necessary on two-feeder units, *i.e.*, one circuit-breaker controlling two feeders, to break the line charging current and care is necessary to ensure that they are capable of this duty. The limiting value of the leading current at zero power factor which can be safely broken will depend on the system voltage. It has been suggested that these isolators should not be used to break a leading current of zero power factor if it exceeds 2 to 4 amperes on 11 kV. or 6·6 kV. systems. The difficulty is not so much the persistence of the arc as the danger of the arc flashing over to adjacent earthed metal. If the isolators are enclosed in sheet steel cubicles then the possibility of flashing over to the steel platework is the limiting factor.

Wherever possible and especially where large fault currents obtain the isolators or links should be so designed that the electro-magnet forces tend to hold them in the closed position. The alternative is to use locking hooks or pins to prevent opening during fault conditions.

Cellular. The term " cellular type " is applied to switchgear in which the components are enclosed in brick, moulded stone or concrete cells. This is usually cheaper than the metal-clad type and modifications may be made without interfering with adjoining units.

The arrangement of the components is simple and straightfoward, the majority being visible on opening the screening doors. The fact of the bus-bars being in air reduces the amount of oil used per unit. The metering current transformers are accessible, which is an advantage when changes are necessary.

Generally speaking, greater building space will be required and erection costs will be higher than with metal-clad gear. The interlocking schemes may be complicated and in medium-sized units suitable access platforms may be found necessary.

In very large switchboards the chief components will be housed in separate cells at different floor levels. Special channels or ducts may be necessary to isolate the main control cables and tee off into each cell separately, thus minimising the possibility of a faulty unit affecting these cables. Fig. 434 gives a typical arrangement. In switch house designs for cellular gear the floors may be supported on brackets fixed in the walls, and are free to slide and so withstand the effects of blast. The roof is also clear of the dividing wall for the same reason.

Cubicle. The whole of the equipment is enclosed in steel plate cubicles with complete or partial sub-dividing barriers. It has been used for units of reasonably high rupturing capacities and is a factory-built equipment having no elaborate structures. The units when assembled as a board present a neat and simple layout and require relatively small floor area. Adequate barriers and suitable isolators, together with safe access, should be provided if it is desired to work on any unit without first making the board "dead." A faulty unit may endanger the adjoining units and the rupturing capacity is rather limited.

Truck. As this term implies, the circuit-breaker is carried on a truck which is arranged to be withdrawn from the main frame or cubicle, either by wheeling or sliding along the floor. In case of failure or want of adjustment a circuit-breaker is easily removed and replaced by a spare unit. Simple interlocking schemes may be used and all the moving parts should be as light as possible, thus tending to limit the size of the circuit-breaker. With the evolution of gas under very severe fault conditions it may be possible for short-circuit to take place on conductors in the same compartment. This again tends to limit the rupturing capacity and it is usually more costly than the cubicle type and may require more floor space. Fig. 435 shows a typical truck unit.

Metal-clad. The principal feature of this type of switchgear is

that all conductors and insulation are enclosed by an earthed metal case. With lower-voltage units the bus-bars are usually left uninsulated in a metal chamber, but on higher voltages compound or oil filling is used.

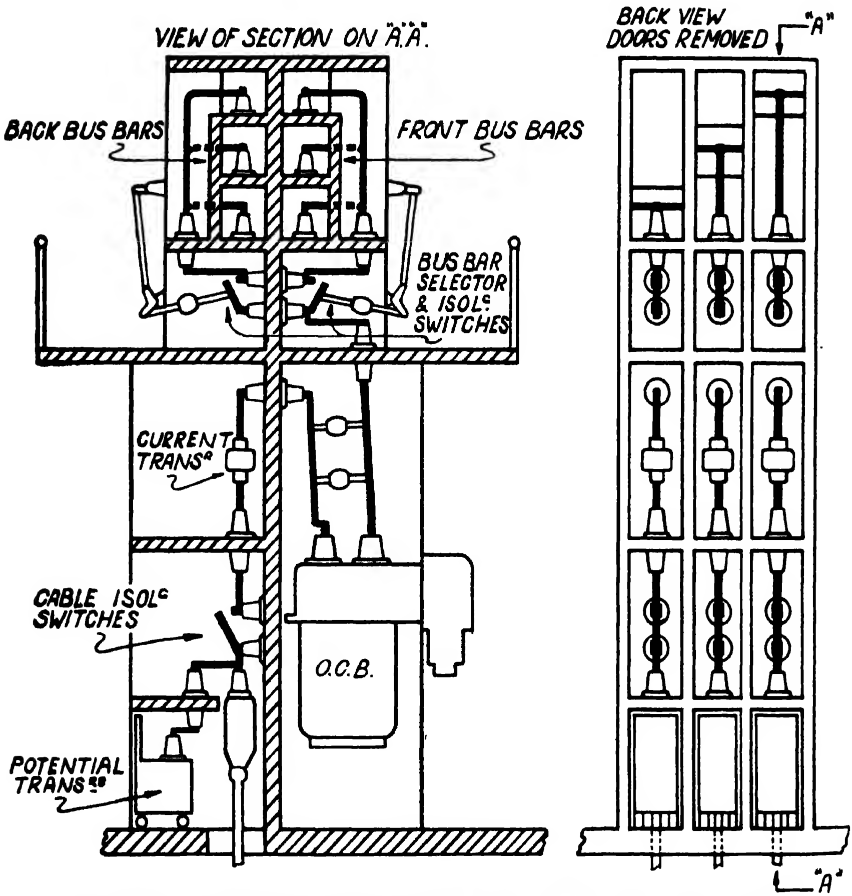


FIG. 434. Stone Cellular Switchgear showing Single Feeder and Double Bus-bars. (B. T. H. Co.)

The units are of sound design and construction and very compact, as the electrical clearances can be reduced when oil or compound are used as an insulating medium. By enclosing all parts in a substantial metal shell having suitable joints it is vermin, moisture and fireproof within certain limits. When oil or compound is used for bus-bar and current transformer chambers care is needed

in the design and construction of these chambers to obviate trouble from leaking joints and it is sometimes difficult and costly to carry out repairs. It is a factory-built unit with consequent reduction in site work. The cost is usually higher than other types, but has the

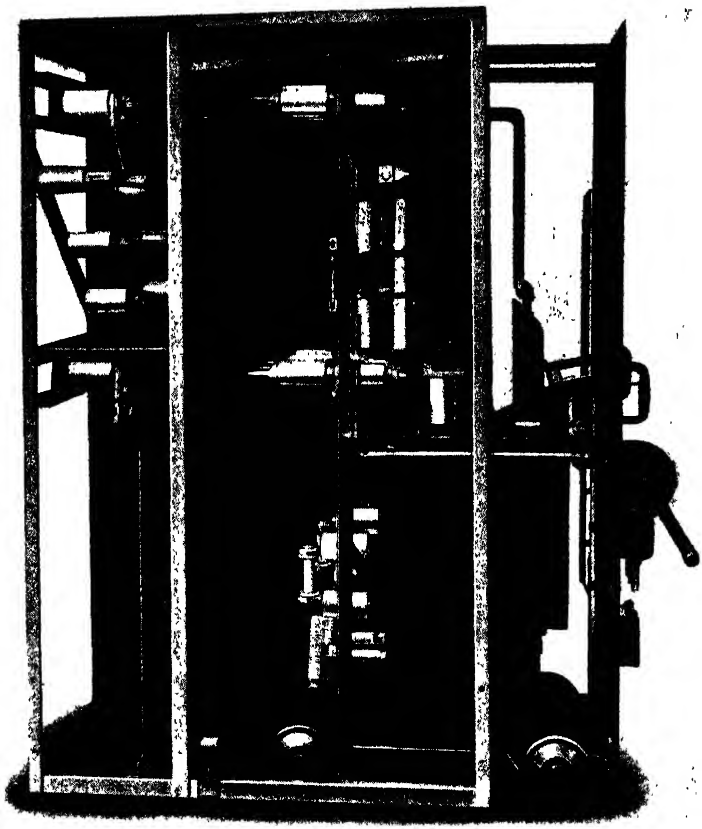


FIG 435. Typical Truck Type Switchgear (English Electric Co. Ltd.).

great advantage in that it is almost foolproof, is simple, and efficient interlocks may be used. A spare circuit-breaker may be kept to replace a faulty unit which is a simple operation.

Metal-clad switchgear may be divided into two classes :—

(1) Horizontal draw-out.
(2) Vertical drop-down.

Both types are popular and are adaptable to large and small units. The second type has been favoured on many high voltage installations for the following reasons :—

(a) Considerable saving in floor space.

(b) A minimum number of loops and joints are required resulting in a stronger arrangement of conductors.

(c) It is more convenient for duplicate circuit-breaker layouts.

(d) Inspection of the circuit-breakers is possible without encroaching on a passage-way.

Transient phenomenon on 33 and 66 kV. metal-clad switchgear has been noted during switching operations. A discharge between earthed components has been noted on 33 kV. gear and is due to high frequency current induced in the metal sheath of the bushing. This spark is a transient which will not impair the efficiency or reliability of the gear.

One type of 33 kV. and 66 kV. 3-phase switchgear has each of its phases separately enclosed in earthed metal and its circuit-breakers are pneumo-oil-operated. In 33 kV. units the insulating medium is mainly gas, oil being used only in the circuit-breaker enclosure, in the breaker and voltage-transformer orifices, and in the pneumo-oil operating system. This switchgear has :

(1) High standard of insulation.
(2) High speed circuit-breaker operation.
(3) Small-oil-volume.
(4) Adequate testing facilities.
(5) Incombustible gas insulation—minimising fire risk.

Typical metal-clad units are shown in Figs. 436 and 437.

Outdoor (*Open*). This type has the advantage that above certain voltages a saving in cost is effected. Buildings are unnecessary except for a control and store house and damage from circuit-breaker explosion is likely to be minimised. The units being placed in the open require more maintenance and, in addition, are liable to damage from lightning and fouling by birds, etc. Wide spacing is necessary and entails a larger ground area. Trouble may be experienced in some localities due to deterioration of insulation caused by pollution of the atmosphere, particularly where soot and salt are prevalent. For particulars of cleaning by water washing see Chapter XXIII.

Outdoor (*Metal-clad*). In recent years metal-clad switchgear for outdoor working has been employed in a number of installations but

has not been generally accepted. Engineers still appear to prefer the indoor type and it has much in its favour. Fig. 438 shows a layout for outdoor service.

Air Blast Breakers. Air under pressure is applied to assist in the

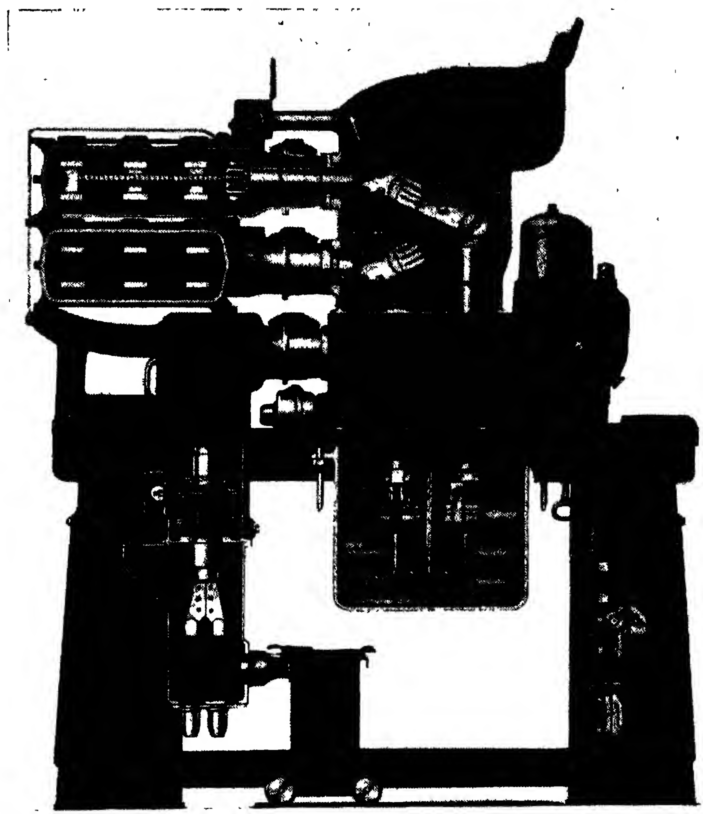


FIG. 436. Cross-section of a Typical Duplicate Bus-bar Horizontal Draw-out Metal-clad Equipment with Off-load Selector Switch. (Metropolitan Vickers Electrical Co.).

making and breaking of the circuit and also affords the desired degree of insulation. The air pressures in use appear to vary from 130 to 300 p.s.i. and air at pressure of about 140 p.s.i. has a dielectric strength comparable with switch oil. This type of switchgear is in commercial service at 3·3, and upwards. The units at 3.3. kV.

having a current rating of from 600 to 4,000 amperes, those at 11·0 kV. a rating of 600 to 1,600 amperes and at 33 kV., 300 amperes. In all cases remote control electro-pneumatic operation is used.

The space occupied compares favourably with standard switchgear and maintenance is simpler and cheaper. The equipment

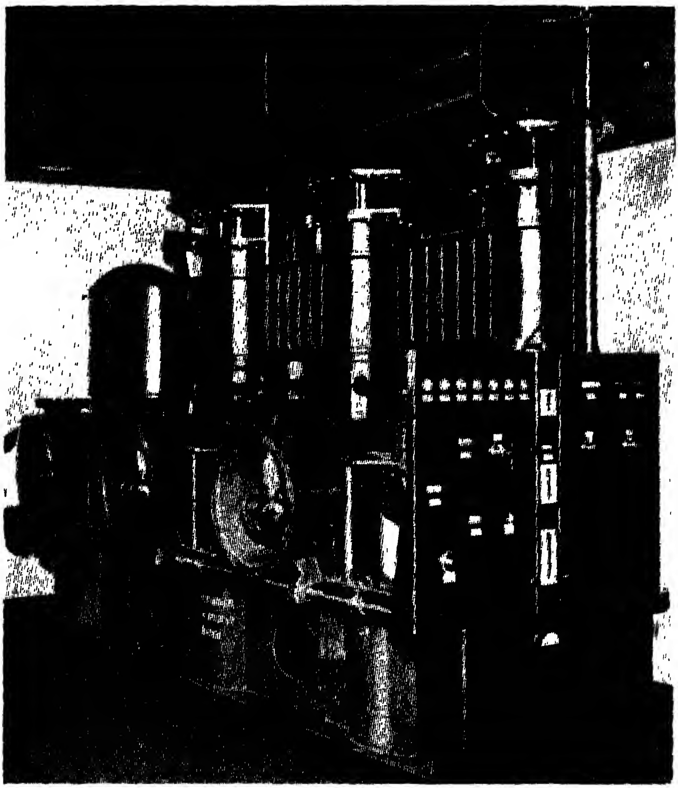


FIG. 437. General View of one Three-phase Unit of 33-kV. Class MS Metal-clad Switchgear with Maintenance Control-panel. (A. Reyrolle & Co. Ltd.)

referred to has operated satisfactorily under severe fault conditions, only the arcing contacts requiring attention. The absence of fire risk is also an added advantage.

Figs 439 to 442 illustrate typical air blast circuit-breakers.

Air Circuit-breakers. For the lower voltage auxiliary supplies it has been the custom to use oil circuit-breakers where the current rating is 300 amps. or more and switch fuses below this rating, the

limiting short-circuit value being 25 MVA. Air circuit-breakers capable of dealing with 35 MVA have been developed and appear to be satisfactory. By using this type oil is eliminated and maintenance is easier. It is claimed that the contacts burn less in air than under oil. When using air-break switchgear in damp situations

TABLE 58. *Switchgear Data*

Type	Voltage kV.	Rupturing Capacity MVA
Cellular (stonework or concrete)	33·0 2·2	1,500 350
Cubicle (steelplate)	15·0 6·6 0·4	350 150 10
Truck	15·0 0·4	250 10
Metal-clad (oil-filled)	132·0 66·0 (outdoor) 33·0	2,500 1,500 1,000
Metal-clad (compound-filled)	33·0 0·4	1,000 25
Air blast	132·0 3·3	1,500 150
Air circuit-breakers	0·6 0·4	35 25
Fusegear	0·6 0·4	35 25

full reliance is placed on sound insulation. The oil-immersed breaker has an advantage in that oil is always present as an insulating medium whereas the air breaker is exposed. For air breakers working in damp situations it is necessary to remove the interior parts for cleaning and drying at regular intervals.

The air circuit-breaker is a form of latched contactor with arc chutes but differing from the ordinary starting contactor in that it is proportioned to deal successfully with 100,000 peak amps. The contacts are of massive construction in order to obtain the desired thermal capacity. Contact is made under pressure from

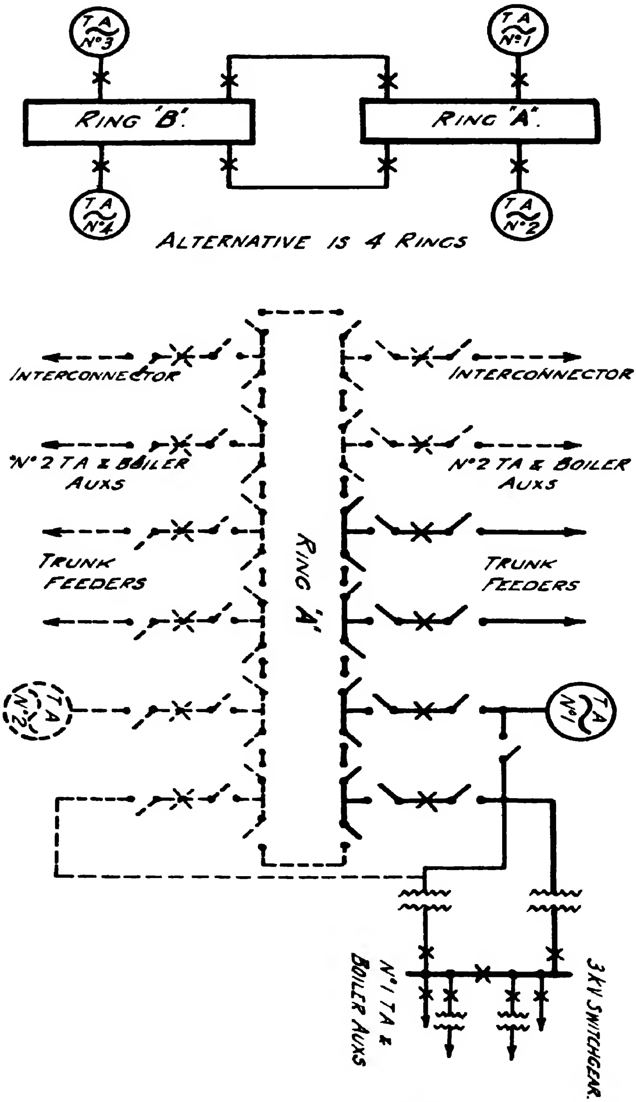


FIG. 438. Outdoor Switchgear Layout.

compression springs which exert 60 to 70 lb. per finger. The arrangement of the contacts is such that the electromagnetic forces are used to increase contact pressure when carrying short-circuit currents. As the electromagnetic forces are proportional to the square of the current these effects are very pronounced at higher values of current. A D.C. shunt trip coil operated through current transformers and a relay, or alternatively series trips of the spring-restrained hinged armature type with time delay device may be fitted. Special attention is given to the design of the arc chutes and it is found that the width of chute should be slightly greater

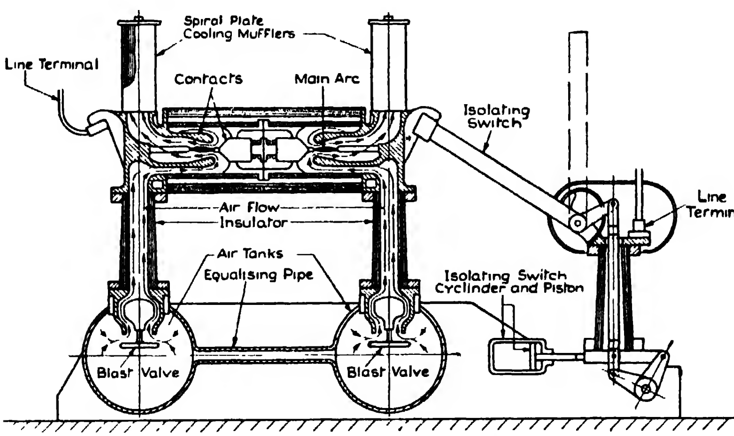


FIG. 439. Diagram of Air Flow in 66 kV. 1,500 MVA Airblast Circuit-breaker. (English Electric Co. Ltd.)

than the diameter of the arc. The circuit-breaker can be either electrically or hand closed and is particularly suited for " direct on line " starting of motors.

Representative data are given in Table 58. Further detailed information will be found in Sub-Station Practice.

Circuit-Breaker Rating. The British Standard Specification 116—1937 outlines the recognised present-day standard and four ratings are mentioned :—

(1) Symmetrical breaking capacity.
(2) Asymmetrical breaking capacity.
(3) Making current.
(4) Short-time current.

One of the most important factors is the overall or total clearance

time from inception of fault to final arc extinction, and this time must include relay and mechanism times. On very large systems, high-speed circuit-breakers are often equipped with high-speed relays, but even here total clearance is quite a few cycles. This feature is important as the asymmetrical current depends on the total time and not the arcing time. The maximum short-circuit MVA which a circuit-breaker can deal with depends primarily on the current it can break. The upper limit is probably in the region of 45,000 amps., so that at a working voltage of 6 kV. the maximum breaking capacity would be $= \dfrac{\sqrt{3} \times 6 \times 45{,}000}{1{,}000} = 470$, say 500 MVA. The upper limits are fixed by economic rather than technical considerations. At the higher voltages of 33 and 66 kV. such heavy currents are rarely encountered. Another point to be borne in mind is the maximum making capacity of a circuit-breaker. If the current to be broken is 45,000 amps. then the possible making current if the breaker is closed on to a fault will be $1{\cdot}4 \times 1{\cdot}8 \times 45{,}000 = 114{,}000$ amps. approx. The factor 1·4 allows for the peak value of the sine wave and the factor 1·8 allows for the possibility of an asymmetrical current wave. The making capacity for remote electrically operated circuit-breakers is generally based on the assumption that 100 per cent. of the D.C. supply voltage is available at the solenoid closing coils. It is difficult to assess a making capacity value to direct manually operated circuit-breakers for so much depends upon the manner in which the closing operation is performed. Providing this operation is carried through without hesitation, the circuit-breakers can be closed successfully on the maximum peak current corresponding to their estimated breaking capacity. The need for power closing of circuit breakers is much appreciated, and for this reason mechanical devices such as the spring-operated closing mechanism is superseding the hand-closing mechanism for circuit-breakers of 150 MVA and over.

It is essential to maintain the closing coil voltage within prescribed limits of the designed figure or trouble may occur. High closing coil voltage (10 to 15 per cent.) may severely distress the circuit-breaker mechanism. As closing coil impulse at 80 per cent. normal coil voltage must be sufficient to close the breaker under short-circuit conditions it is apparent that a higher voltage impulse on no-load is of a very high order.

Design and Constructional Details. The design and construction of circuit-breakers varies so much that it is impossible to cover in detail even some of the most important features. Some of the

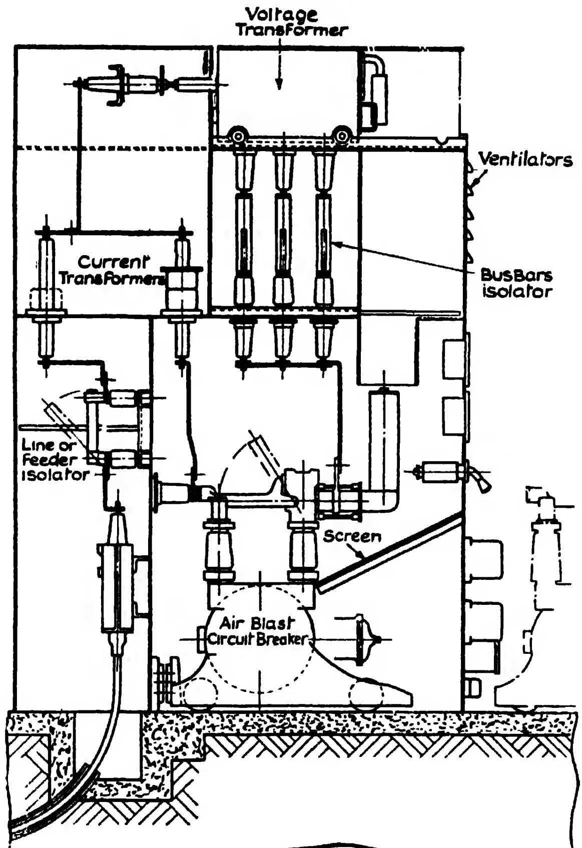


FIG. 440. 11 kV. 500 MVA Air-blast Circuit-breaker Equipment in Sheet-steel Cubicle. (English Electric Co. Ltd.)

principal features in the design of circuit-breakers and associated equipment are :—

(1) Contacts and all current carrying conductors should be of ample thermal capacity to carry maximum fault current without undue heating.

(2) Contacts to be such that the contact pressure is improved with the fault current passing and also provide adequate contact and thermal capacity at the instant of making contact on the peak value of the fault current and so prevent dangerous heating.

(3) All conductors should be of robust construction and adequately proportioned to withstand any electro-mechanical forces.

(4) The operating and contact lifting mechanisms should be of ample strength to deal with the throw-off forces due to the electro-magnetic effect at the peak value of fault current.

(5) The design and construction of the supporting framework and standards should be such as to withstand all mechanical forces which may be imposed upon them. If cast iron is used the construction should be such that it is always to resist compressive forces, mild steel being used where tensile forces are likely to be imposed. To resist electro-magnetic forces the layout of conductors should be such that loop formations are as few as practicable.

(6) Solenoid, pneumatic or other closing device should be of adequate power to close positively and rapidly against any electro-magnetic forces. Pneumatic operation is more rapid than electrical operation. A battery is still required to control air flow valves but is much smaller than that usually required.

Testing stations are now available for proving certain sizes of switchgear but some of the higher ratings cannot be tested at full voltage and current in existing testing plants. The circuit-breakers are usually of standard design unless any special conditions have to be met. There are numerous designs of contacts in use and explosion pots are almost universally adopted on large circuit-breakers.

After being in service for a while it is sometimes found that heating takes place due to oxidisation which commences to form on the surface of the contacts. It has been suggested that this can be overcome by silver-plating the contact fingers as this would reduce the contact resistance. Further, any oxidisation of the silver contacts would not bring about any great increase in the contact resistance since the oxide of silver has a contact resistance about the same as the original silver surface. The tanks are of mild steel boiler plate and top plates cast iron, cast steel, malleable iron, bronze or welded steel boiler plate, depending on the current rating and the rupturing capacity. Non-magnetic inserts are sometimes used in steel covers to minimise hysteresis losses. Lining for the tanks may be elephantide, plywood or other similar material. Steel phase-barriers, unslotted, and extending the whole way across the tank are sometimes used. These form a continuous metal barrier between phases below oil and shield the arcs magnetically and also increase the strength of the tank.

Bus-bars may be of the oil, compound filled, or condenser bushing types for higher voltages, whilst bus-bars in air are suitable for the medium and lower voltages. Condenser bushings may be

tested by means of a Schering bridge for power-factor and watt loss.

Cases are on record where discharge has taken place in 33 kV. bus-bar spouts and also at a clamp on the bars themselves although failure did not occur. In the latter case the bus-bar is insulated to a thickness of about $\frac{3}{4}$ in. between conductor and earth and has eight

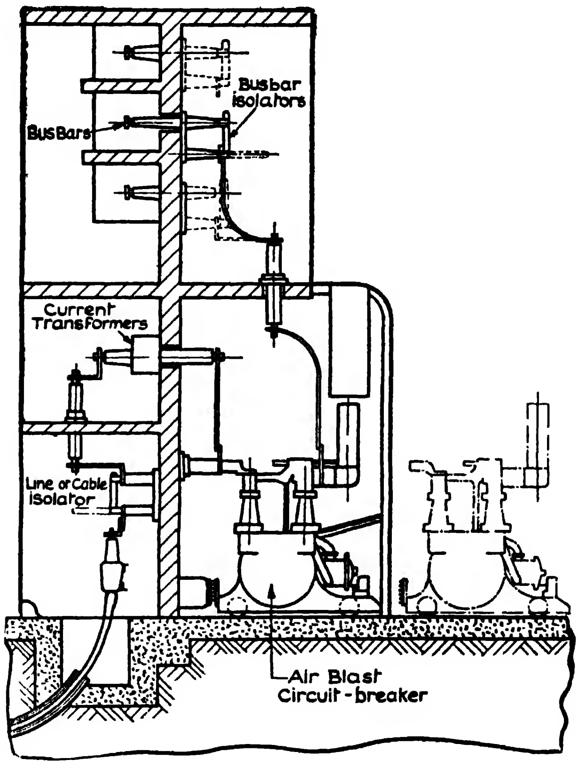


FIG. 441. 6·6 kV. 350 MVA Air-blast Circuit-breaker Equipment in Stonework Cell. (English Electric Co. Ltd.)

dielectric layers the outer layer being earthed with a copper sheath 0·015 in. thick with 0·077 in. binding wire of tinned copper. The surface density and "action points" concerning conductors subject to voltage are referred to under "Lightning," Chapter XVIII.

Complete phase separation is desirable on large switchgear and means of obviating hysteresis effects and circulating current

should be provided. Facilities for periodical testing of the insulation of high-voltage bus-bars may be included. It should be possible to isolate the circuit-breaker of any unit completely from the bus-bars and outgoing circuit. The isolating devices are interlocked with the circuit breaker so that the isolators cannot be operated until the circuit breaker is open, and the circuit breaker cannot be operated unless the isolators are either fully closed or fully open. Sometimes such incorrect operations result in nothing more serious than tripping out of a set or bus section, but in some cases serious personal injury occurs and perhaps considerable damage to equipment. Interlocks which may be electrical and mechanical devices must be simple and above all reliable. "Castell" figure keys and locks are quite common and have simplified interlocking schemes in addition to being comparatively cheap. The interlocking system is effected by means of figured locks which are incorporated in the circuit-breaker operating mechanism, isolating switches, etc. Each numbered lock can be operated only by the key bearing the number relating to the lock. At the switch house one key only is provided bearing any single number.

Earthing devices should also be included. It would appear that a safe and reliable earthing procedure should provide :—

(1) Effecting earthing operations by means of extension contacts on the circuit-breaker unit thereby enabling the operation to be performed through the breaker itself and affording protection to the operator.

(2) Feeder and bus-bar shutters arranged for separate control when required so that "live" spouts can be protected while carrying out tests on dead conductors or working in the immediate vicinity.

Access to each phase of each outgoing circuit for the purpose of Megger, current or voltage tests is provided for by including testing sockets. A further set of testing sockets or other means for plugging in may be provided on the other side of the current transformers in each phase so that testing current may be injected through the primary of the current transformer for protective gear testing. Testing sockets for testing any two complete 3-phase panels are usually provided.

The secondary circuits of each set of instrument transformers should be earthed at one point only and arranged so that each circuit can be disconnected from earth for testing purposes without breaking any normal current circuit.

Voltage transformers should be connected so that they are included in the protective zone of the circuit with which they are

associated and be arranged to avoid risk of danger to the operator.

Maintenance. A rigid maintenance programme should be adhered to and the results accurately recorded, especially such items as : items inspected and tested, adjustments or replacements effected, engineer responsible and date.

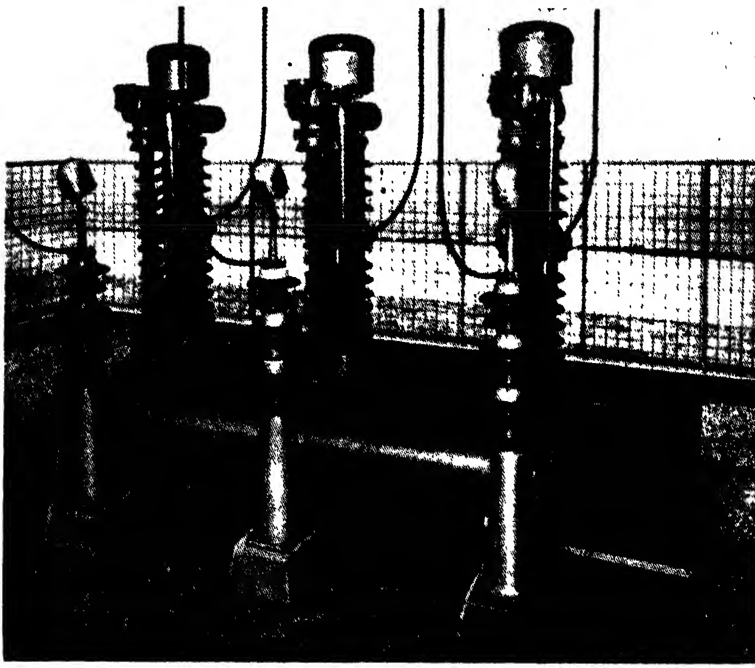


FIG. 442. 66 kV. Class OAB Air-blast Three-phase Switchgear Unit mounted on a Concrete Plinth and surrounded by an Earthed Screen. (A. Reyrolle & Co. Ltd.)

Switchgear maintenance may be broadly divided into two sections : (1) Electrical, which includes insulation, current capacity, arc control and extinction ; (2) mechanical, which includes physical operation of the various components.

Above 11 kV. periodic power factor tests on all insulation is suggested and accurate records will indicate any deterioration in the insulation value of bushings, separators and post insulators, etc.

Switch Houses. The design and construction of switch houses will depend to a large extent upon the type and layout of switchgear adopted. It is desirable that the architectural features should

be in keeping with the main buildings but under no circumstances should the essential principles be forfeited to attain this. Ample space should be provided to facilitate erection, operation, inspection and maintenance of any portion of the equipment.

Although various materials have been used in the construction of switch houses the most widely favoured appears to be brick and concrete with steel framework for larger buildings.

Steel framework covered with patent glazing has been used to secure lightness and saving in time of erection and the cost also compares favourably with that of other materials. This method of construction provides better natural lighting and also withstands fire reasonably well.

Considerable thought has been given to the possibility of attack by enemy aircraft and in this respect precautions must be taken to deal with blast and splinters from bombs bursting in the vicinity. No possible attempt could be made to design switch houses to resist a direct hit from a high explosive bomb.

With high-capacity plants it is almost essential that the switchgear layout should be divided into sections, both physically and electrically, if complete shut-down is to be avoided. The sections should be in separate compartments and so connected that each section can be energised independently. In some installations a compromise is effected by enclosing the bus-bar section switches in separate chambers or cells. The most effective method is to have separate switch houses although the provision of two bus-section switches (or one bus-section switch and one isolating switch) is a sound alternative since both sections may be isolated in the event of fire. These layouts are illustrated in Fig. 443. The sectioning walls, which are of brickwork or concrete, should be of adequate thickness and preferably carried the full height of the chamber. Any doors leading to adjoining chambers should be of fireproof construction and if practicable of the self-closing type.

A circuit-breaker failing to clear fault current may explode and cause serious damage to the building. In one failure a side wall and an end wall of a building which contained a large proportion of the switchgear were blown out so allowing the roof to fall and cause considerable damage to the healthy circuit-breakers.

Where steelwork is used in the construction of the switch houses as in the case of main building columns and beams, this should have fire protection. A simple method of preventing distortion and twisting is to encase all columns and beams in concrete. To make

a steel-frame building fire-resisting it is essential to provide such protection to the steelwork that will delay for a few hours the attainment of an injurious temperature. In large chambers it is preferable to use some form of moulded asbestos protection. This does not disintegrate under the action of fierce or unevenly applied heat as concrete does, and, further, is considerably lighter and easier to apply. Switch houses should be of substantial construction and comply in all respects with the Electricity Regulations made under the Factories Acts 1937 and 1948 and the Electricity Supply Regulations (1937).

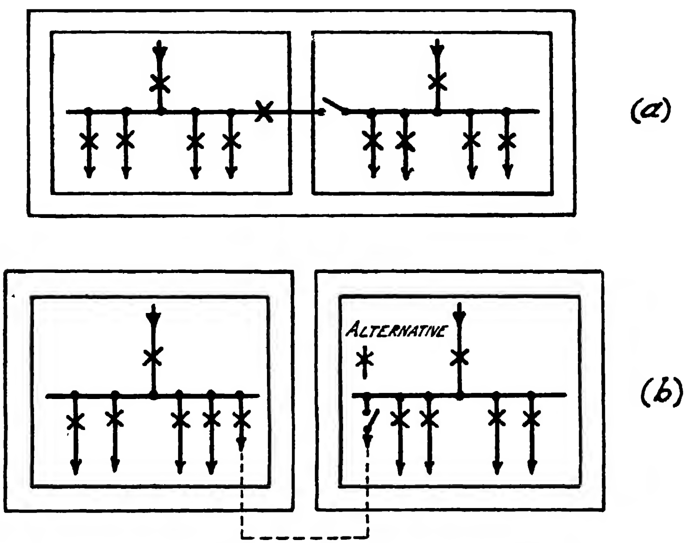


FIG. 443. Suggested Switchgear Layouts.

Windows, doors and other openings should never be left unfastened if there is any danger to persons and they should prevent the ingress of driving rain and drifting snow.

Flat reinforced concrete roofs with asphalte covering are quite common. On large chambers hollow steel beam construction has been used, the roof being finished off with a $\frac{7}{16}$-in. layer of insulating board and seven-ply patent felt roofing in bitumen.

A damp-proof course of blue bricks, bitumen or other suitable material should be included in all walls (see also Chapter XXIII.). The thickness of roofs, walls and floors will depend on the loading required. Walls will normally be from 14 to 18 in. thick.

Switch house floors should be designed for oil drainage as it is desirable that any oil which may be released through a switch tank exploding or other failure (busbar current and voltage transformer chambers) should be quickly drained from the chamber to prevent spreading if on fire.

It may be argued that failure of circuit-breaker tanks is a rare occasion, but experience indicates that some provision should be made for dealing with any oil which may escape.

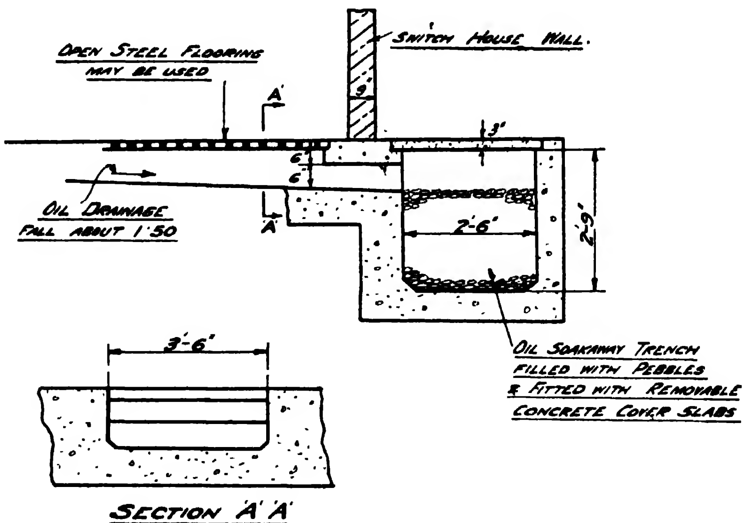


FIG. 444 Detail of Oil Drainage for 1,500 MVA Units.

Various methods are to be found in practice, some of which are :—

(1) Arranging the floor to have a slight fall towards a longitudinal trench running the entire length of the building, the trench being filled with sand, chalk, pebbles or granite chippings and covered with open steel grating.

(2) Providing large chases or troughs (Fig. 444) in the floor immediately below each circuit-breaker. The troughs should have an adequate fall, 1 in 40 would suffice, towards a trench or sump outside the building.

(3) Fitting a cast-iron drain pipe below each circuit-breaker and connecting it to a sump. The floor immediately below the circuits would fall to the drainpipe in hopper formation.

The second method may be further improved by filling the whole area of the trough with pebbles and then covering with open steel flooring. This has the advantage of reducing the temperature

of the hot oil and may actually reduce it below ignition point. The burning oil will be broken into streams and cooled in passing through pebbles and free access of air is prevented. Where drain pipes are used these may be led out individually or connected to a header serving all units and then taken to a common sump outside the building.

The pipes should be protected by a metal guard or screen to a level above the pebble filling and should also be trapped. If they are run out separately to an outside pebble-filled trench a guard will also be required at this end. The sumps can be emptied by portable hand pumps. Pebbles used for fillings vary in size, a satisfactory aggregate being 50 per cent. ½-in. mesh and 50 per cent. 2-in. mesh.

In some cases an oil sump is unnecessary as any oil likely to be released would drain away effectively into the ground. If, however, the site conditions are such that flooding is probable, considerable hydraulic pressure may be produced in the surrounding ground and any oil left to seep away would be brought to the surface. This would aggravate matters in the event of fire during this period.

Probably the most suitable floor is 1 in. to 2 in. granolithic paving on concrete for the main floors and concrete only for basement floors. Basement and ground floors are of reinforced flat-slab construction. Care should be taken when designing switch house floors to allow for the worst possible loading conditions. For example, a three-phase (single tank) 33 kV. 750 MVA oil circuit-breaker would be about 7 tons " dead " weight, but under fault conditions the equivalent " dead " weight may probably be in the region of 24 tons. This is a point of importance when designing switch houses, particularly where basements are immediately below the switchboards.

A reasonable number of windows should be provided and, if possible, so designed that they are internal or, alternatively, protected by hanging steel shutters on the outside of the building. This is to prevent damage by blast or splinters. Concrete or brick blast walls are useful, where windows are in the outside walls. A suggested layout is shown in Fig. 445. A large proportion of the windows should open outwards to release any air pressure in the building caused by ignition of explosive gases. Experience has shown that it is possible even with relatively small oil circuit-breakers for explosions to occur and cause considerable damage to buildings unless some form of safety valve is included. Adequate window space in the form of roof lights or, alternatively, side

windows high up in the walls are suitable. With windows in the side walls and placed above the level of the switchgear the possibility of damage from bomb splinters or missiles is reduced. The majority of the windows can be of the fixed type, but it is desirable that

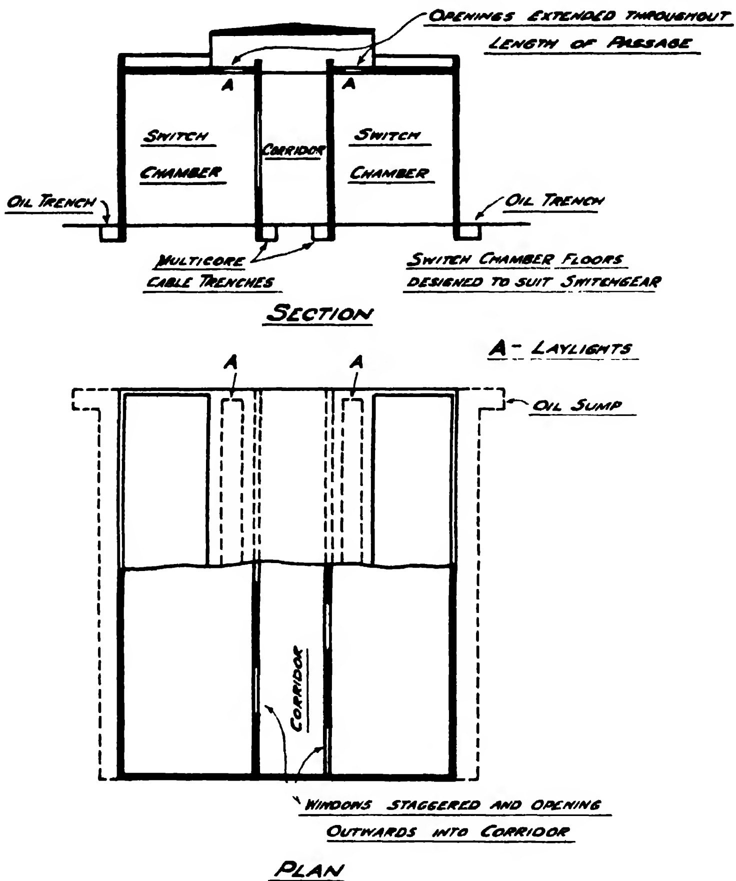


FIG. 445. Suggested Layout of Switch Chambers to provide for Internal Explosion and External Blast and Splinters.

certain sections be hinged to swing outwards and normally held closed by counterweights but not latched. The inclusion of windows may dictate the form of fire-fighting equipment to be used, for if the windows are blown out there is usually considerable draught caused by the fire which may reduce the effectiveness of inert gas as a fire-fighting medium. Glass in switch house roofs may be in such

a dangerous state after an explosion or fire that it may be necessary to remove it before the full extent of any damage could be ascertained. Where possible all doors should open outwards, and consideration should be given to the provision of suitable oil traps at the threshold of all doors in division walls.

Where the switch house is divided into chambers and basements each should have two exits to comply with the appropriate regulations. If possible the emergency door should be placed at the opposite end of the chamber to the main door and should only open from the inside and be unlocked. The door handle should be large enough to facilitate quick opening in case of emergency.

Very large doors should include a wicket door. Special self-closing fireproof doors of light construction should be provided between any adjoining chambers. Roller shutters are preferable for very large external doors.

Another feature of considerable importance is that of cabling, and this can be simplified by providing a cable room, basement or race directly below the switch chamber. When switch chambers are at ground level a basement with tunnels or cable pipes leading therefrom is the general practice. Should the switch chambers be above ground level a basement is still desirable and the cables may be racked and taken out on structures in the form of bridges. To complete the separation this cable basement should also be sectionalised in a similar manner to the switch chambers. In some installations the switchgear is in two banks arranged back to back and the cables are led down into a reinforced concrete basement in which the cables are laid in reinforced concrete ledges cast as part of the wall. These two cable-ways are joined together into one at the end and are then continued outside the building. The multicore cables are all laid in single tiers on pressed steel trays. By providing a basement the main cables can be handled with ease, while auxiliary supply and control cables associated with the switchgear can be taken direct from their respective units into the basement, thus keeping the switch chamber free from cabling.

There has been a tendency to keep basements to a minimum size and incorporate a pebble-filled oil-well in the switch chamber floor. The cables are kept clear of this well, separated by fire-proof barriers then taken into a small basement or culvert. In some cases basements have been entirely eliminated, the cables being laid in pebble or sand-filled trenches in the switch chamber.

All holes in the switch chamber floor for the passage of cables

and pipes into the basement should be effectively sealed to prevent ingress and spreading of burning oil into the basement. In the event of fire the cables may be melted and drop into the basement leaving clear openings for the passage of oil. Various methods of sealing (Fig. 446) have been adopted, some of which are :—

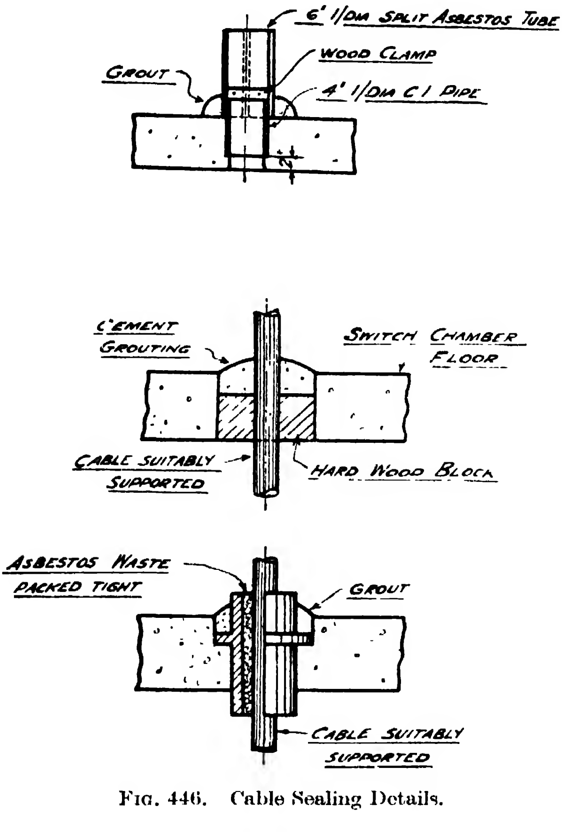


FIG. 446. Cable Sealing Details.

(1) The insertion of hard wood blocks grouted up with cement which can be easily broken if necessary.

(2) Packing the space tightly around the cable with asbestos waste or other similar material and grouting with cement.

(3) A split asbestos tube with wood clamps and a cast-iron pipe insert projecting through the floor.

(4) Building a brick chamber around the cable in the switch chamber and filling with dry sand. The sand used should be burned as ordinary sand contains too much moisture.

Before grouting up any lead-covered cables they should first be surrounded with clay.

Other features of importance are the heating and ventilation of switch chambers. The maintenance of a constant temperature is desirable to prevent breathing and moisture condensation. The measurement of relative humidity is very important as it affords information as to whether any slight fall in temperature will cause condensation of moisture. Relative humidity is sometimes expressed as a fraction and sometimes as a percentage, *i.e.*, when air is found to contain one-quarter as much water vapour as would be required to saturate it, the relative humidity may be expressed as 0·25 or 25 per cent. The relative humidity is determined by finding out to what temperature the air must be cooled in order that the moisture present will suffice to saturate the air. This temperature is found by cooling the air until it begins to deposit moisture and is known as the dew point. The use of the wet and dry bulb thermometers as explained under Cooling Towers, Chapter IV, Volume I, will enable the relative humidity to be estimated. The room temperatures recommended are outlined in Chapter XVI.

The insulation resistance of any insulation (such as switchgear spouts and insulators) exposed to the atmosphere is affected by the humidity and it is essential to maintain this at a reasonably safe level. The degree of ventilation will influence the humidity and the fact of raising the temperature only by heating does not reduce the amount of moisture present in the atmosphere. Warm air may contain a higher amount of moisture than cold air and there is danger that greater condensation would result should the temperature fall suddenly. The ideal would be for the heating to be accompanied by ventilation provided the humidity of the incoming air to displace the outgoing is not too high. Such a condition may arise where the switch houses are very near cooling towers.

Adequate ventilation is essential to carry off any moisture condensing on the walls and plant and more especially in the case of newly-constructed buildings to remove the moisture coming from the masonry. To ensure good ventilation the inlets should be near the floor of the chamber and the outlets near the roof. The desideratum of a good ventilator is that it should effect a constantly changing air, have no moving parts and no running costs. For efficient air conditioning the air in a chamber should be completely changed to suit conditions obtaining.

Some types of louvre ventilators are fitted with fire seals, the louvres closing when the seal breaks. Where simple types of wall ventilator or air grates are included a fine mesh expanded metal or wire guard should cover the whole area. Sliding or hopper types of damper may be incorporated to regulate the air inlet as desired.

It is common practice to install some form of electrical heating in switch chambers with or without thermostatic control. In view of the large area of the chambers and the numerous obstructions of masses of steel and other metal, it appears that heaters over which air is blown by fans is desirable. A combination of this method and water heating may be used. The hot water is taken from the surge tank line in the turbine house, control equipment being provided where necessary. If low pressure steam is available this may be used.

A disadvantage of wall radiators—low temperature tubular or other types—is that convection air currents draw particles of dust and carry them upwards to be deposited on the walls and any nearby apparatus. Where heaters of this type are used they should be placed below the inlet openings near the floor of the chamber. The cold air entering the chamber will form a cushion above the warm air drawing it inwards towards the switchgear and allowing it to rise gently in the right place.

The number of lighting points will depend on the size of chamber and usually good general lighting will suffice. An adequate number of plug points should be included for wandering hand lamps.

In order to carry out repairs to switchgear an inspection bay common to all switch chambers should be provided, this can also serve as an unloading bay for transporting and erecting the gear. If the switchgear is very large it may be justifiable to have an overhead crane in each chamber to facilitate erection and maintenance. In addition, it is often an advantage and sometimes a necessity to provide a switch truck for handling switch components.

CONTROL ROOM

The modern power station has grown to such proportions that the question of control has become of primary importance and deserves careful thought throughout the early stages of the station design and layout.

As far as the electrical side is concerned, the control room, or

operating room as it is sometimes termed, has become an important feature of the power station. The control of the mechanical plant may also be undertaken from this room and remote control of certain portions is provided to assist operation during emergency. Remote control of certain main steam and feed valves is useful in times of emergency in view of the difficulties likely to be met in gaining access to many of these valves. The steam and feed valve emergency control panels may be enclosed in a special case or compartment normally locked. This control may be arranged for both opening and closing of the valves, but usually the latter operation only is catered for. Such remote control is very useful in the event of a burst pipe as it would be almost impossible to approach the valves.

The control room accommodates the electrical control and metering equipments associated with the turbo-alternators and feeder switchgear, together with all auxiliary apparatus relative to control and operation. By housing these equipments in one room control is centralised, and its location, layout and general design deserve special attention.

The interconnection of large power stations has introduced among other problems that of control and it has been realised that centralised control of an area is essential for efficient operation. To meet the technicalities arising in connection with the transmission of instrument readings and circuit-breaker positions the developments which have taken place in the light current electrical engineering industry have played an important part.

Systems used for multi-circuit telegraphy over a single telegraph line have been utilised so that the area control engineer has before him instruments showing current, voltage, power, etc., at various points on a scattered transmission system, together with an automatically operated circuit diagram indicating the positions of the important circuit-breakers. All this may be achieved automatically through the single telephone circuit normally used to give verbal instructions to those in charge at these stations.

The adoption of television equipment to control room equipment may become a practical proposition in the near future.

Location of Room. The location of the room in relation to other sections of the station is of importance and a suitable position should be obtained.

In many stations of earlier days, particularly when the steam engine was the prime mover and even after the advent of the steam

turbine, the control board was on the engine house floor or in the boiler house—wherever sufficient space was available. Sometimes a small platform or even a handrail served to separate the control board area from the remainder of the engine house.

This was far from an ideal layout; when trouble occurred (for example, when a steam joint blew, a machine ran away, or there was some other unusual or untoward occurrence in the vicinity) the attention of the control engineer was likely to be distracted from the control board and from the system under his care. The next step was to place the control board on a gallery or platform alongside a wall in the engine house. This was a slightly better arrangement, as it increased the distance between the control engineer and the machines and had a further advantage in that it permitted an unobstructed view of the whole of the turbine house. The following is an extract from an early specification: "The switchboard shall be erected so that every part is readily accessible and shall also be placed in such a position that the operator commands a view of the machines controlled. The switchboard shall preferably be mounted on an elevated fireproof platform."

It was still necessary, however, that there should be easy, and in those days direct, communication between the switchboard operator and the engine attendants. Another fact to be borne in mind is that due to the small capacity of the machines the controlling switchgear would also be small and therefore did not require much space. Although the open bus-bar system took up a good deal of room, it fitted easily beneath the control board gallery itself.

In some of the smaller stations the control board is still to be found on a platform in the turbine house, the switchgear being housed in an annexe away from the main buildings. This arrangement of control board in a large station would result in a board almost as long as the turbine house which would have many disadvantages from an operating point of view, apart from the question of space and appearance. Where a station is commenced on a small scale it may not be justifiable to build a separate control room in the first instance. In such cases the electrical control and metering equipment of the turbo-alternator as well as that of the high voltage outgoing feeders may be located on the turbine house operating floor so as to be readily accessible to the turbine operator. This is only a temporary arrangement and the equipment would be relocated in a control room when the station capacity reached a figure demanding a separate control centre.

The removal of the control board to a separate room has been made possible largely by the introduction of communication and signalling equipments, together with the advent of steady turbine drives.

Modern stations with their large generating units have brought into being the need for larger switchboards with consequent complexity of switching, and this again has justified placing the control board in a separate room. With the adoption of electric control for large switch units the location and arrangement of the control board proper is not affected by that of the switchgear. Therefore remote control has assisted to further the claims of an isolated control room, the disadvantage being the expense of multicore control and instrument cables that are necessitated by such a layout. For economy and convenience in cabling, the control room should be situated near the switch-houses and, if possible, have easy access to the turbine house.

In view of the experience obtained during wartime conditions it has been considered a decided advantage to place the control room away from the main buildings, and regulations under air raid precautions specify such a position. Consideration has also been given to the construction of underground control rooms in view of the developments in aerial warfare. To meet the fire hazard it is desirable that the room should not be placed directly above a switch house, and if it adjoins provision should be made to limit the spread of fire.

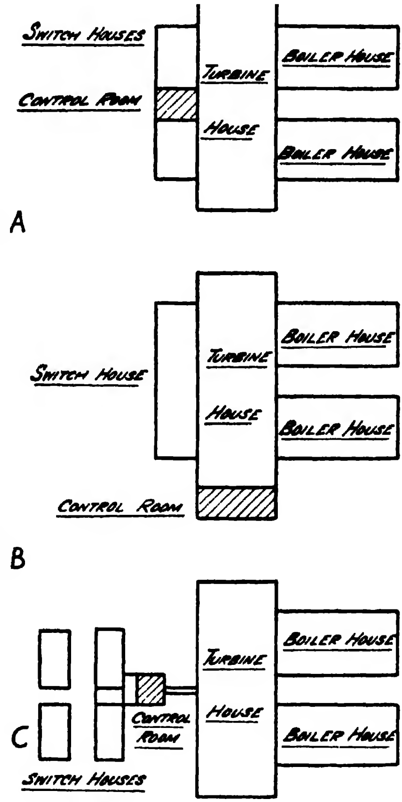


FIG. 447. Position of Control Room Relative to other Sections of Plant.

The location depends upon the layout and orientation of the station, and Fig. 447 shows how this can be arranged to suit the

plant of which it forms part. Generally, the control room is adjacent to the turbine house, but there are cases where it is isolated from it. When it is adjacent to the turbine house the control room may be either at turbine house floor level or overlooking it some height above.

Probably the layouts that have best proved themselves with time could be arranged under three headings :—

(1) Isolated from turbine house but having telegraphic and telephonic communication between the control room, turbine and boiler houses, also having easy access to the switch-house and turbine-house.

(2) Adjoining turbine house and having full or part vision of the machines with telegraphic and telephonic communication between the control room, turbine and boiler houses.

(3) Adjoining turbine house and having visual and audible connections without telegraph and telephone equipment. These equipments only being used for the boiler houses.

Control rooms in large stations usually come under the first and second. Wherever the control room is situated it is advisable to pay due attention to the general approach both as regards access and cabling for much unnecessary work will be avoided not only in the early stages of construction but more so as the station grows.

Design and Layout. Although a separate room has been provided it is only too evident that in many cases little attention has been paid to the amenities or arrangement of the room. To achieve an ideal arrangement it is essential that there should be co-ordination of design between the architect and manufacturer, the control room and the control board and their co-related apparatus. To obtain some idea of the final layout and originate suggestions before construction a full-scale model of the room and boards may be built. A number of cardboard instruments placed in position on the model boards give some idea of the general assembly and also of the light reflection problem. In this way it is possible to avoid alterations in building construction, instrument assembly and control panel dimensions which would hold up completion in the later stages of erection. Further, a suitable lighting scheme may be selected and provision made to include all distribution boxes, control points and fittings. Such a procedure assists the engineers, architect and manufacturers to visualise the completed room more easily than is possible from drawings. Probably the best layout is that in which the control panels or board are part of the room construction, or what might be termed a room within a room. This arrangement ensures privacy, quietness and cleanliness—

the essential features for high operating efficiency The control room is usually well lighted with part-glass roof and occupied by the linear or semi-circular operating switchboard for the feeders and alternators. Figs. 448 to 451 illustrate layouts. The architectural features should be such that both the mental and physical effects assist the control engineers to maintain concentrated interest in the job.

Sound-proofing and noise elimination, as applied to the control room, not only serve to increase operating efficiency but undoubtedly

FIG. 448. Control Room. The Electric Heater is suspended from the Ceiling. Dunston "B" Power Station.

have a beneficial effect on the general health and mental condition of the control engineers. The room, however, should not be absolutely sound proof as this would give a "padded room" feeling which is undesirable. As long as the extraneous noises are not too distracting and do not interfere with telephonic communication there is no need to take precautions to obviate them.

A control room should have at least one clear glass window in a side or back wall as a view from such a window can be very restful after a period of concentration on the control board. Windows overlooking the turbine house should preferably have

double-glazing to minimise the transmission of noise to the control room.

Special attention should be paid to the construction and decoration of the room. It does not follow that a room which pleases the occasional visitor is ideal for the control engineers to work in. The walls, ceilings, floors, control board and instruments should be of colours that are restful to the eyes. The colour scheme of the walls and control board should be so planned that the diagrams and

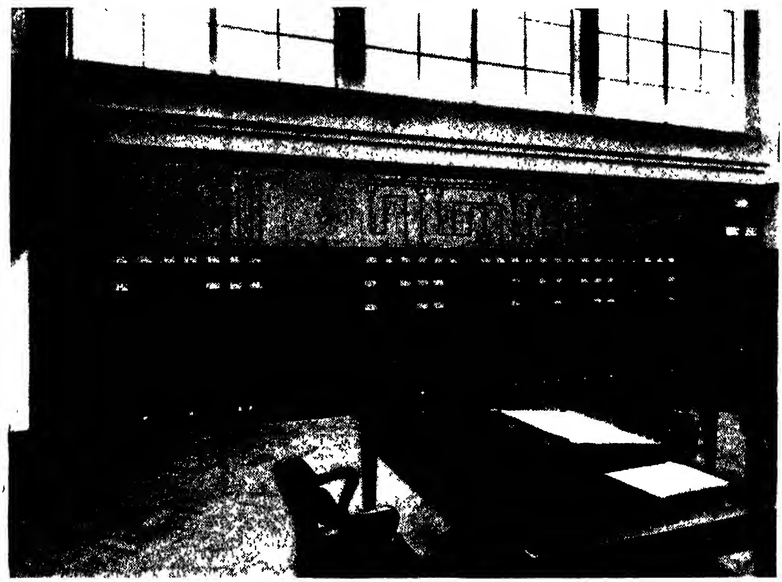


FIG. 449. Control Panels, Dunston "B" Power Station. The Lighting Cornice is immediately above the Panels. (A. Reyrolle & Co.)

instruments stand out clearly against their background, making selection easy for the control engineers. Large areas of dark colour should be eliminated as they absorb too much light, and further, dark areas tend to confuse the eye in its rapid movement from light to dark. The decorative features of the ceiling and floor for this reason should be quiet and subdued. Wood floors of oak or teak blocks may be used, or alternatively a plain linoleum of quiet tone.

It is essential to provide an even diffused light, both natural and artificial, of adequate intensity but with a total absence of glare. Use has been made of well-designed ceiling lighting such as laylights which provide natural illumination by day and in which are

housed the lighting units to provide illumination at night. The disadvantages of this method are the large amount of energy consumed and the necessity for maintaining the internal glazing in a clean condition otherwise the illumination falls off considerably. Further, in the event of war, damage from enemy aircraft is possible and glass is unsafe for the operatives. Such factors are all worthy of attention when designing a control room. Should the position

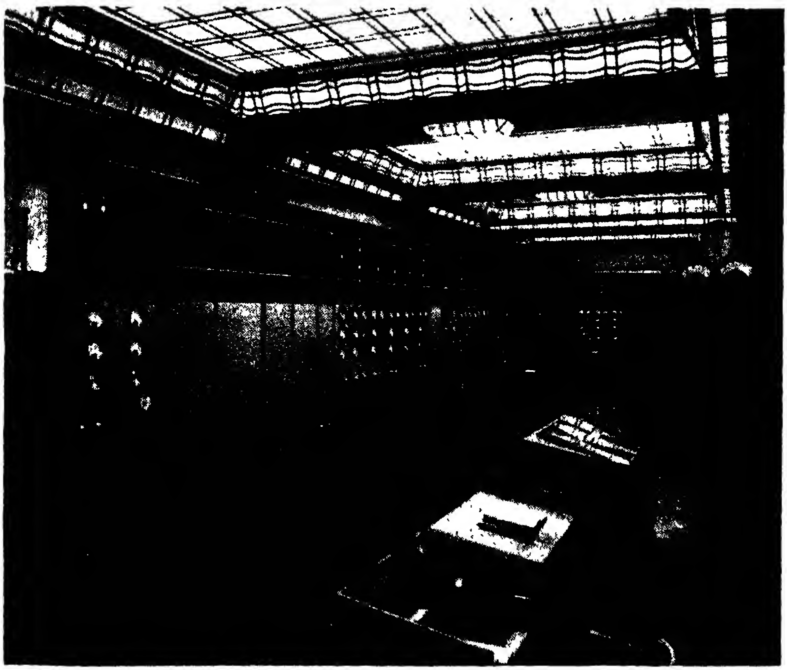


FIG. 450. Control Room, Battersea Power Station.

of the control room be such that it is likely to be affected by a low-setting sun, it would in all probability be advisable to blank off the west side, that is, if there is a fairly large window space or lantern.

Care should be taken to eliminate reflections from instrument faces and bright surfaces. With the intensities correctly proportioned, the control engineer should be able to look up from white paper on his desk and see the control board immediately, without having to wait for his eyes to become accustomed to a different

intensity. Even with indirect lighting it may be necessary to tip the upper part of the control board slightly forward to clear the top instruments of reflections.

The heating and ventilation of the room should give a healthy atmosphere and be dust-proof and draught-proof. Electrical space-heating in the form of low-temperature tubular heaters controlled by thermostats may be used, or as an alternative a hot-water system with calorifier.

Where the outside atmosphere is liable to be dust laden it is advisable to install ventilation plant which will include an intake fan and air filter. Air would normally be drawn from outside the building, passed through a filter and then taken *viâ* sheet metal ducts to discharge openings in the control room ceiling. In the event of an air raid or gas attack the intake can be closed and the air in the control room re-circulated after passing over trays of special chemicals to purify it. Arrangements are made for the air to leak from the control room through continuous openings between the top of the control boards and the underside of building structural beams into the surrounding relay board chamber and also through fanlight openings above the doors.

Where indirect lighting is adopted it may be found that the heat provided may exceed that normally covered by the heating installation.

A complete air-conditioning plant may be installed to provide warmed or cooled air at comfortable relative humidity with positive ventilation and filtration of both fresh and return air for the control room. By re-circulating the majority of the air a saving can be made on the power consumed for heating purposes, but the extra cost of the re-circulating duct would offset any saving in the initial cost of the plant.

In estimating the capacity of the ventilating plant for service in this country, the external and internal temperatures may be taken as 32° and 65° F. respectively, whilst five changes of air per hour may be assumed and no allowance made for re-circulation. A station in Calcutta has air-conditioning plant installed for the purpose of treating the air in the control room not only from the operator's point of view but also to maintain the small wiring in good condition under adverse climatic conditions. The conditions aimed at are a dry-bulb temperature of 80° to 82° F. with a relative humidity of 60 per cent. This high dry-bulb temperature was chosen to ensure that the temperature in the control room is at all

times slightly higher than maximum outside dew-point temperature, which sometimes approaches 80° F., the object being to avoid condensation settling on the equipment and wiring in the event of unforseen circumstances which would permit of outside air being admitted. A large slow-speed fan suspended from the ceiling keeps the air in motion. The entering air temperature is therefore kept within limits which are not unpleasant and an adequate air movement during warm weather is provided. As silence is essential, the air flow velocities in the ducts should be kept within reasonable limits and a velocity of 10 ft. to 15 ft. per second is usual for duct-work, but the inlet and outlet velocities should be much lower to avoid draughts and noise.

The layout of the control boards and pedestals should have a neat and simple appearance. This however should be consistent with ease of operation during normal and emergency conditions, and the equipment should occupy a minimum of floor space. With a view to simplicity and facility for extensions the various control panels may be arranged so that it is possible to change the feeder controlled by any individual control panel. In large stations where there are numerous sections to be assembled to form a board it is not possible to have the whole board under observation from one position. It therefore becomes impossible to adopt the linear arrangement. If the board has not of necessity to be under observation from any one position, then the linear arrangement can be adopted. An argument put forward in favour of this layout is that the control engineers have to patrol their control boards and this tends to break the monotony.

The duties of a control engineer will vary according to the output of the station and also in no small measure to its position on the system with which it is connected. He may have to deal with fluctuations of load due to the geographical position of the station which may be the inter-connecting point of two supply areas and on account of load transference between or synchronisation of areas. Further, tap-change equipment on main substation transformers usually requires frequent operation and often necessitates re-adjustment of plant excitation and voltage. Operating difficulties may be encountered due to system surges and there may be unstable running conditions resulting from leading power factor caused by the capacitance of long overhead lines. A fault may occur on a system causing a heavy surge with consequent drop in voltage and tripping of auxiliaries (both A.C. and D.C. drives if

the latter are fed from converters) resulting in a drop of steam pressure. The high-voltage network voltage may fall momentarily to 3,000 volts (6,600 volts normal) and rise immediately to between 7,000 and 8,000 volts and after a few seconds fall to normal. Such conditions may arise where a transmission line or interconnector has a high capitance loading resulting in a leading power factor of probably 0·98 or thereabouts.

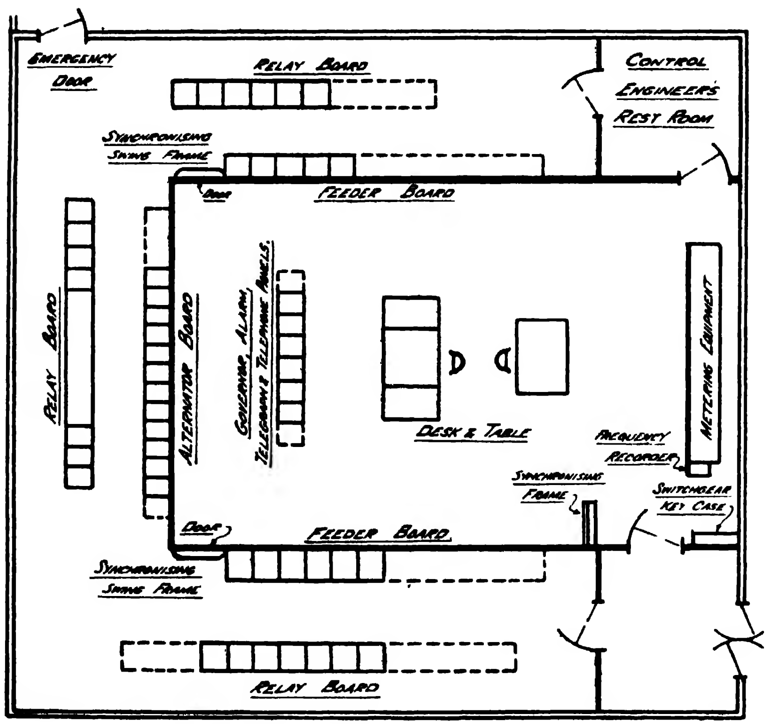


FIG. 451. Layout of Control Room.

When observation of the complete board is desired from one position then the semi-circular or horse-shoe arrangement may be employed. The disadvantages of this lay-out are that it requires a large floor space and board construction and erection costs are higher than the linear arrangement.

If careful thought be given to the selection of only essential control devices and instruments to be kept under continual supervision, it will be found practicable to adopt a modified form of

control board layout. Such a layout is shown in Fig. 451 ; here straight sections of control panels are grouped and sectionalised so that the advantages of a semi-circular board are obtained without its higher cost. The floor construction to suit this layout is shown in Fig. 452. Feeder-control panels are arranged along two sides with the alternator panels across the end and separated from the feeder panels by the synchronising panels. The synchronising panels may be placed at an angle or left straight. The board can also be arranged to form a crescent with the bus-section and common instrument panel in the centre, the control panels corresponding to the main switch panels being grouped symmetrically on either side. In the common instrument panel a clock, summation power factor meter and summation wattmeter can be mounted in trefoil fashion. The question as to whether the whole of the control boards should be under complete observation from one position has been freely discussed from time to time ; this, however, is not the whole solution of the problem.

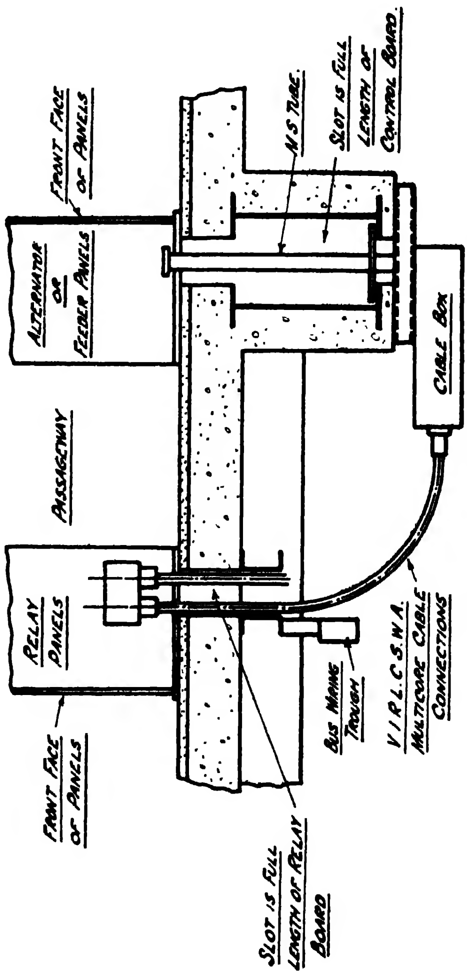


Fig. 452. Arrangement of Terminal Boxes under Control Panels.

Intelligent grouping of control units is of first importance. The various pieces of apparatus should be arranged in accordance with their importance, thus keeping the central control features immedi-

ately before the control engineer. Lines of sight and avenues of approach both have to be taken into consideration, and a compromise effected between a layout having ample space and giving clear unobstructed access and one having limited spacing with consequent restricted access.

Due to its flexibility and reliability, remote electrical control has been almost universally adopted and has a further advantage in that it eliminates the restrictions of space and location associated with mechanical operation.

Whatever arrangement of control equipment is adopted, the features of visibility, accessibility and avoidance of confusion under all conditions of operation should be borne in mind. Intelligent grouping of apparatus together with a layout conducive to the control engineers reacting automatically in any combination of circumstances is highly desirable. The control switches should be about 4 ft. 6 in. above floor level and the instruments so placed that when the control switch is operated the control engineer has them in full view. The instruments should be assembled so that their purpose is readily apparent.

The selection of the type of control panel and the assembly of the various apparatus thereon depends primarily upon the mode of operation. Where more integrating instruments and protective relays which need only occasional inspection are required than can be arranged properly on a control panel, it may be possible to have them mounted on separate panels placed directly behind the control panels. These are termed overflow or relay panels and may be grouped in similar formation to the alternator and feeder panels.

An alternative arrangement is to have panels with front and back mounting faces in which case the integrating meters and relays are mounted on the back. A reasonable space should be left between the control and relay panels to form a passage way to give access to the wiring, terminal boxes and fuses. The passage should be well lighted, and each panel in the form of a cubicle should be enamelled white inside and have a lamp to light automatically on opening the access door. By adopting such a scheme the control engineer has only the essential operating features before him upon which he may concentrate.

It is usual to provide a mimic diagram or replica of the switchgear arrangement; this may take the form of a separate board or may be arranged directly above the control panels. Indicating lamps or semaphores are provided to show the operation of circuit

breakers, isolators and earthing switches. A sheet steel mimic diagram panel finished dull black, or according to the colour scheme desired, and fitted with aluminium strips to form a representation of the various circuits has been used. Hand-operated semaphore indicators enable a visual record to be maintained of the circuit breaker and isolator positions in each circuit. A white lamp in each of the diagramatic circuits glows if the circuit trips automatically. Red and green signal lamps on each control panel automatically indicate the position of a circuit-breaker. In one type the operating panels are made of laminated glass and the sides and rear of sheet steel. A striking design is that which appears as clear lines and symbols on sheets of opaque plate glass. The several parts of the diagram, corresponding to the various circuits, are illuminated by coloured lamps fixed in partitioned boxes behind the plate glass, the different colours indicating the electrical condition of the circuits and plant.

A special relay indicating desk with a sloping glass top divided into suitably lettered panels below which indicating lamps are fitted may be included.

In the event of a circuit-breaker opening automatically, the corresponding panel on the desk is illuminated and indicates which relay is responsible for the action of the circuit-breaker. Use may also be made of the turbine room wall where this adjoins the control room to provide a system diagram which is flush mounted on the wall and an observation bay to overlook the turbine operating floor is helpful. Attention should be paid to the selection of instruments for control board mounting, as these are very important during normal and emergency operating conditions. A high degree of accuracy would be defeated if readings were rendered difficult by unnecessary markings, or if essential information were omitted. A separate control room, particularly remote from the turbine and boiler houses has a great influence on the instrument and relay sensitivity, and also reduces maintenance charges. Where such apparatus is mounted on panels in the turbine house, vibration plays havoc with delicate bearings and other sensitive parts. Vibration can be minimised by the use of rubber washers and packings, but by placing the control panels in a separate room these troubles are overcome. Other troubles are those due to temperature variations causing condensation and resulting in rusting and deterioration of relays and instruments. Panel wiring is also affected by condensation.

The instruments should be of sound and simple design, and so arranged on the panels as to readily be seen and selected at will. Nameplates or labels designating the various instruments and points of measurement, etc., should be plain but conspicuous. Special attention should be paid to scales, pointers and general appearance. Numerous designs of instruments are on the market, and although the projecting type held priority for many years these have been largely superseded by the flush mounted type. This type enables the instruments to be arranged to the best advantage on the panels, gives a more pleasing appearance and is easier to keep clean. It is possible that future stations will see the advent of miniature instruments for use in almost all services.

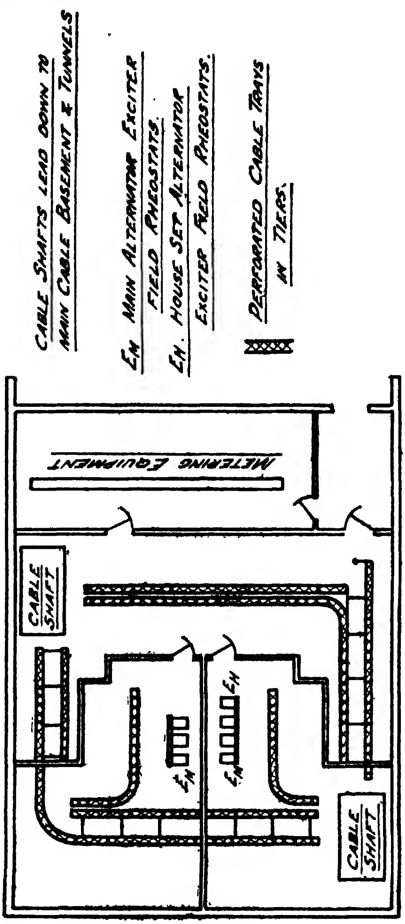


FIG. 453. Layout of Control Room Cable Chamber.

The application of visual signals should be extended and developed, and the use of audio signals limited as is consistent with operating efficiency. Visual signals should not deviate much from the eye level as viewed from the normal operating position.

The panels may be of steel plate and angle framing of the self-supporting cubicle form having an approved enamel finish to tone with the colour scheme of the room. Sheet steel panels having black matt finish with a bright black beading and instruments with bright black bezels relieves the uniformity of the dull black background and presents a pleasing and simple appearance. Grey finish is also popular. In America steel panels have in some cases been

superseded by five layer weather and fireproof plywood faced with special material on both sides, making a total thickness of about 1 in. Adequate access should be provided to permit of easy inspection and maintenance of the various pieces of apparatus.

In most cases separate desk panels or pedestals are provided for governor remote control, exciter field-rheostat operating gear, telegraph and telephone equipment. These can be arranged either in a straight line or semi-circular formation, and placed a reasonable distance from the alternator control board and synchroscopes. The desk type of board does not always lend itself to easy making-off of multicore cable terminations or general maintenance. From these desks the control engineer can vary the load on any set and at the same time keep the other sets under view.

Where interconnectors are in use the control switches for transformer tap-changing may also be mounted on an adjoining desk to facilitate the distribution of the load between the interconnectors and alternators.

The inter-connection of stations to other private systems, as for example the "grid," has entailed the installation of separate metering equipment to record the import and export of power to or from a station. This equipment may be placed in the control room or located in a separate room nearby.

The control engineer should have some idea of the steam conditions obtaining, so that a machine can be put into service as soon as possible. This can be obtained by connecting a transmitter on each steam receiver to a pressure indicator in the control room. In some stations the main boiler and turbine stop valves are arranged for remote electrical operation from the control room. Panels for fire protection indicators and testing switches may also be included. One layout includes a manual control panel which carries an alarm bell and section indicators. Should a trip operate the alarm is sounded and a red lamp glows to indicate the section involved. If any particular trip is locked out of commission for adjustment or while work is being carried out in the switch-house a white lamp indicator gives notice of this. Local manual operation is possible, so that if anyone is present when a fire breaks out the equipment can be immediately put into operation.

The supplies to the tripping and closing solenoids for the main circuit-breakers are very important circuits, and it is advisable to provide a voltmeter for indicating the D.C. supply.

Where possible all apparatus should be on the same floor level

and preferably in the same room, whilst floor obstruction in front of the control boards should be avoided.

Cable Basement. When fixing the position of the control room, provision should always be made for a basement or chamber immediately below. This is essential to accommodate the many control cables and conduits to and from the switchgear and alternators. By providing a basement or terminal room the cables can be handled and arranged with ease and the control room is free from congested groups of cables. The wiring is separated in the terminal boxes, and then rises to the associated control and relay panels immediately above.

Control and instrument wiring constitutes a vital link and is worthy of careful consideration. The majority of the cables are of the lead-covered single-wire armoured multicore type, and may be arranged on special racks or laid on perforated sheet-iron trays. The latter method has the following advantages :—

(1) A large number of circuits may be accommodated in a relatively small space by arranging the trays in tiers.

(2) It is very flexible in that it can be extended to suit any particular type and size of cable and provision may be made for extensions without any alteration to existing structures and trays.

(3) All cables are accessible, thereby facilitating inspection and location in case of faults.

(4) Comparatively low initial cost.

The layout of the trays may be arranged to follow the control boards, the cables and conduits being taken direct from the trays to their respective panels. The cables should be subdivided into groups and sectionalised in such a manner that interference in the event of fire is reduced to a minimum.

The cable chamber should never be allowed to become a store for spare cables, etc., each passage way being kept clear to give unobstructed access to all sections.

In some cases the exciter field rheostats have to be placed in this chamber and if sufficient space is available there is no objection to this arrangement. Figs. 452 and 453 show typical layouts.

System Control Room. With the smaller power stations of earlier days supplying comparatively simple transmission systems it was the general practice to have a senior operator or switchboard attendant in the station to take charge of any abnormal situation which may arise. With the continued growth of interconnection of small and large power stations and the resulting complicated networks

came the necessity for a specialised organisation to deal with electrical load control. The " Load Dispatcher " system was introduced in America about 1903 to carry out this work and to ensure re-establishment of supplies under abnormal conditions with the minimum of delay. In this country such a system of control was adopted about 1906, the first of which was probably that of the Newcastle-on-Tyne Electric Supply Co. under the title of " System Control Engineer." The system control room is usually situated centrally with regard to the system although the administrative centre or head offices of the supply authority are often a favoured position.

The major power station control room may also be used for this purpose and has many advantages. A large wall diagram is provided on which the distribution and transmission lines, essential circuit-breakers and generating and transforming plant together with earthing points are shown.

The object in the design of such an electrical diagram should be to obtain simplicity, avoid cross-overs and arrange power and substations as geographically correct as is possible. The colour scheme of the diagram is of considerable practical value and is worthy of detailed thought. The markings on the discs may be arranged to convey useful information, *e.g.*, a red disc may denote a circuit-breaker is closed and a green one when it is open. If the red disc bears a small white centre it denotes that breaker is closed on overcurrent protection, the actual setting of the relay being noted on another white disc nearby. Different discs can be used for other forms of protection, etc.

Indicating and recording instruments are provided to enable the operating engineer to note kW. load on each station and the voltages on the system. The recording instruments give a continuous graph of the transmission voltages and the system frequency. The summating wattmeters and the voltage indicators are very useful under all operating conditions and the frequency indicators are indispensable when stations have lost synchronism with one another due to system troubles.

Telephone equipment is often in duplicate, permitting either of two control engineers to operate any selected portion of the system. To ensure continuous communication, avoid delays and facilitate operation it is often desirable to provide a ring line to each transforming or other substation in each district which is connected to the system control room. Such an arrangement provides many

reliable circuits of communication. An emergency lighting system is also essential in this room.

Control Panels and their Equipment. Each circuit-breaker equipment should be provided with a control panel (Fig. 454) upon which all operating and indicating devices and important instruments associated with control are mounted. To keep the control panels within reasonable dimensions and so reduce the overall length of the control board, each panel should have a relay or overflow panel. This panel may be placed immediately behind the control panel and would accommodate all relays and integrating instruments. In some installations a compromise has been effected by making the back of the control panel suitable for mounting the relay and integrating instruments.

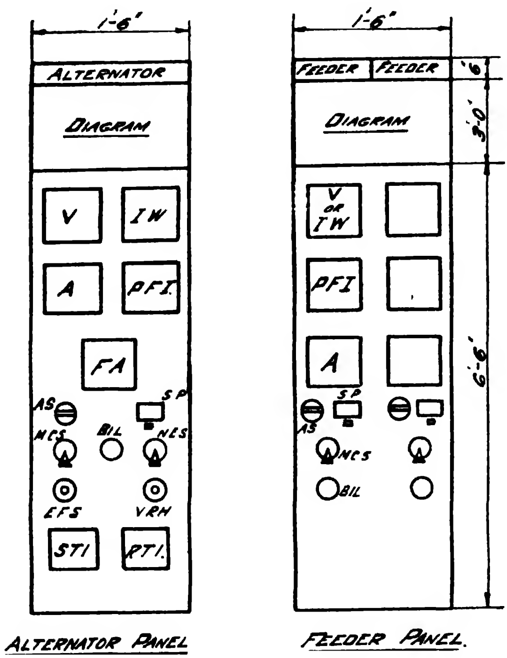


FIG. 454. Arrangement of Alternator and Feeder Panels.

V—Voltmeter.
A—Ammeter.
FA—Field ammeter.
PFI—Power Factor Indicator.
AS—Ammeter Switch.
SP—Synchronising Plug.
MCS—Main circuit breaker switch.
BIL—Battery indicating lamp.
EFS—Exciter field switch.
VRH—Voltage regulator handwheel.
STI—Stator temperature indicator.
RTI—Rotor temperature indicator (if required).
IW—Indicating wattmeter.
NES—Neutral earthing switch.

A further panel or desk is provided for each alternator equipment upon which the governor control switch, exciter rheostat control switch and transmitter for the turbine house telegraphs are mounted. An alternative is to mount these switches on the control panel and have an independent telegraph pedestal. The desks are arranged to face the alternator control panels and may be grouped in linear or circular formation. The circuit-breaker control switch is arranged

to operate in one direction when closing, and in the opposite direction when opening. All control switches should be designed to avoid inadvertent operation with provision for locking in the open and closed positions.

A case is on record where a house set alternator was out of service for overhaul with the bearing keeps off and the control

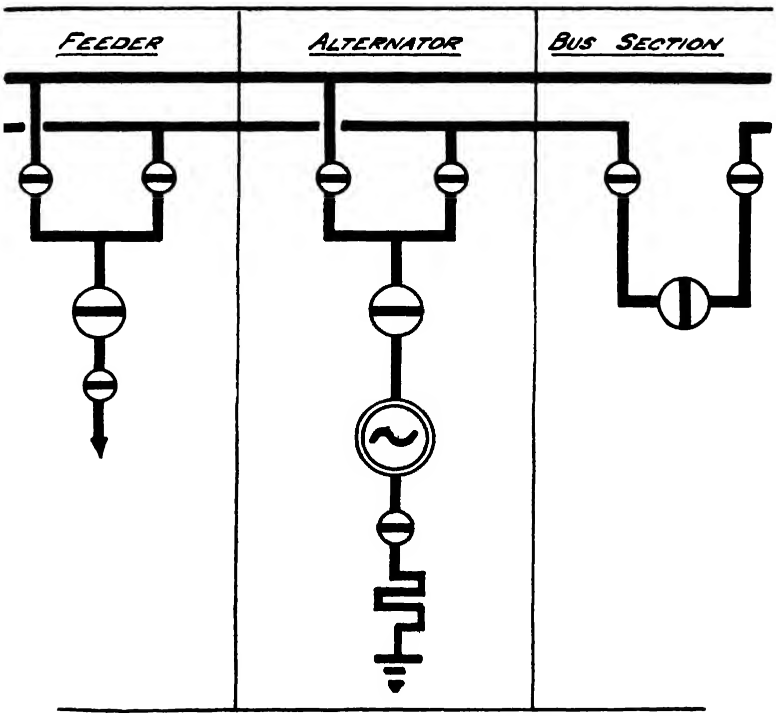


FIG. 455. Control Panel Diagram with Semaphore Indicators.

switch was closed, putting the alternator on to the bus-bars. The alternator circuit breaker should have been racked out and the control switch on the panel locked in the open position.

The operating handles of the control switch may be interlocked by a Castell key system to prevent operation of the control unless the bus-bar isolators are in the correct position.

Where synchronising apparatus is included the connections between the control switch and closing relay coil of the circuit-breaker should be completed through a receptacle bridged by a synchronising plug, so that it is impossible to close the circuit

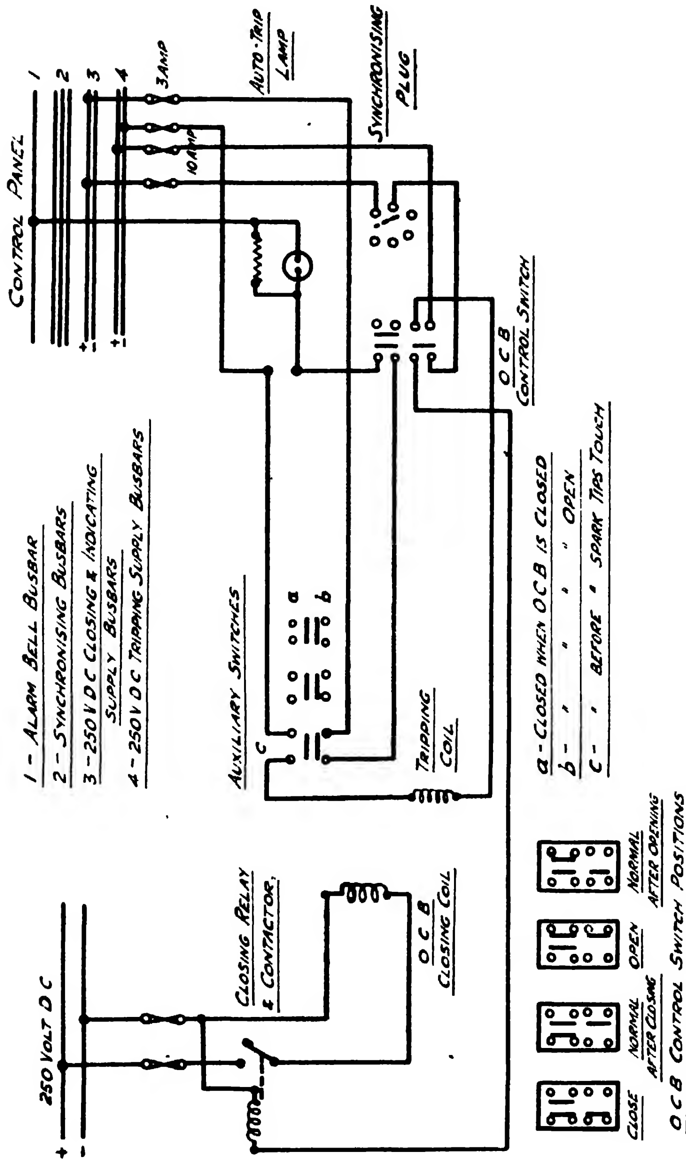


Fig. 456. Switchgear Closing and Tripping Circuits.

breaker until the plug is inserted in its corresponding synchronising receptacle.

An indicating panel (Fig. 455) may be mounted above the con-

trol panel to show automatically by means of lamps or semaphores the positions of the corresponding circuit-breaker and its isolators. In the case of an alternator the positions of the field suppression switch and neutral circuit-breaker may also be shown. The indicating panel should include in diagram form the main electrical connections of the equipment it controls.

Auxiliary bus-bars should extend the full length of each control board to serve the following :—

Synchronising connections (A.C.).
Tripping circuit (D.C.).
Closing circuit (D.C.).
Alarm circuit (D.C.).
Pilot lamp indication (A.C.).

Each control panel is supplied as may be required from these bus-bars through fuses (Fig. 456). Probably the best way of ensuring supply to the tripping circuits is to have links in the individual panels instead of fuses. Both fuses and links are to be found in practice but the latter appears to have advantages. Complete supplies to a cubicle should be isolated by withdrawing the fuses and links of that cubicle.

An adequate number of terminal blocks should be mounted in each control panel to serve all multicore and other cables.

A common alarm bell gives audible warning in the event of a circuit-breaker tripping automatically. It should be possible to open the bell circuit at the corresponding control panel to stop the bell ringing without affecting the remaining circuit-breakers. When the tripped circuit-breaker is again closed the bell circuit should be automatically set to give warning. It should be impossible to open the bell circuit when the breaker is closed. The alarm circuit has a relay which brings the alarm bell into operation in the event of a circuit-breaker opening automatically. A lamp is included in each panel which lights when the circuit-breaker is tripped automatically and in this way the control engineer will readily ascertain which circuit is open, and take steps to restore supply with a minimum of delay. An alternative is a Neon lamp on each panel connected across the protective relay terminals of the corresponding trip circuit and shows that this circuit is at full voltage. The lamp is shorted when the relay operates and serves to indicate the circuit-breaker affected. The lamp current is insufficient to operate the breaker trip coil but glows with full brilliance if battery voltage is normal.

In some cases two electrically-driven clocks are fitted, one operating continuously, while the other stops automatically with the sounding of the alarm bell, the exact instant at which a fault occurred can then be logged at the convenience of the control engineer and the clock restarted. Red and green lamps indicate circuit-breaker in closed or open positions. To prevent breakage due to vibration, etc., indicator lamps may have specially constructed filaments.

The instruments should have long and clearly-divided scales with pointers large enough to be easily read from a distance of about 15 to 20 ft. All instruments and apparatus for control panel mounting should be back connected and have terminals and removable links to permit of portable testing sets being connected.

It is possible to connect the main ammeter to measure the current flowing in any of the three phases. Synchronising is carried out between voltage transformers installed in the alternator, feeder and other equipments on the side of the circuit-breakers remote from the bus-bars.

Synchronising voltmeters, rotary synchroscope and lamps are included. The main voltmeters are connected in circuit by means of the synchronising plug or voltmeter plug of any panel equipped with a synchronising voltage transformer. If an automatic voltage regulator is installed it may be either on the control panel or overflow panel. A main field ammeter is also included in the control panel equipment.

A typical set of equipment for a large turbo-alternator is as follows :—

Ammeter, voltmeter (common meter is sometimes used), indicating wattmeter, integrating watt-hour meter, power factor indicator, frequency indicator (common meter is usual), auto-trip lamp (white), voltmeter receptacle, synchronising receptacle, oil circuit-breaker control switch (open (green) and close (red) indicating lamps), governor motor control switch, exciter rheostat motor control switch, mimic diagram which would have indicators for selector isolating switches, main circuit-breaker and neutral circuit-breaker. A pilot lamp showing that the tripping circuit supply (D.C.) is intact is also desirable.

This equipment could be mounted on a combined flat and desk-type panel, although alternative arrangements are usual.

Other items which may be mounted on a separate panel are :—

Main field ammeter and voltmeter, single-pole field switch, motor-operated main exciter field rheostat (behind panel), voltage regulator with associated relays, contactor, adjusting rheostat and change-over switch.

Single-pole earth leakage relay (self-reset), three-pole overcurrent relay

(self-reset), circulating current protection relay (hand reset), inter-tripping relay (hand reset). Field suppression switch (mounted near alternator).

If a separate alternator control board is provided as is usual with semicircular or square board layouts, the two panels in the centre may be arranged to control bus coupling, bus section and neutral earthing and immediately above these panels the steam receiver pressure gauges may be mounted. Another feature is the mounting of the voltage regulators inside the cubicles behind a hinged glass frontal panel. The exciter field rheostats which may be operated from handwheels on the alternator panels can be mounted above the control board on stays extending from the cubicle framework to the wall, the operation being by chain or bevel drive. An alternative is the use of motor drive with remote push button or switch control. A separate panel may be provided to accommodate a frequency indicator, voltage recorder and synchronous clock so that comparison may be made of system frequency with standard time.

Another useful feature which may be included is an ammeter for the D.C. closing current of the main switchgear. An ammeter is provided for each closing circuit, one per annexe or section of switchgear. Assuming three annexes then three remote ammeters would be mounted on the corresponding panels in the control room. Should the closing relay contactor stick in the " close " position, the ammeter will show that the closing coil is still energised and the control engineer can take steps to cut off the closing circuit supply. The closing coils are only short-time rated, and a burn-out will result if they remain energised.

Some particulars relating to various coils are given :—

33 kV., 750 MVA, 400 amps. O.C.B. :

Main closing coil . .	96 amps.—250 volts. D.C.
Closing relay coil . .	1·1 ,, ,, ,, ,,
Trip coil . . .	2·8 ,, ,, ,, ,,

6·6 kV., 500 MVA, 3,000 amps. O.C.B. :

2 Main closing coils (in parallel). .	70 amps. total—250 volts D.C.
2 Closing relay coils .	2·2 ,, ,, ,, ,, ,,
1 Trip coil . . .	2·8 ,, ,, ,, ,, ,,

Much will depend on the types of mechanism used and the details vary for each make.

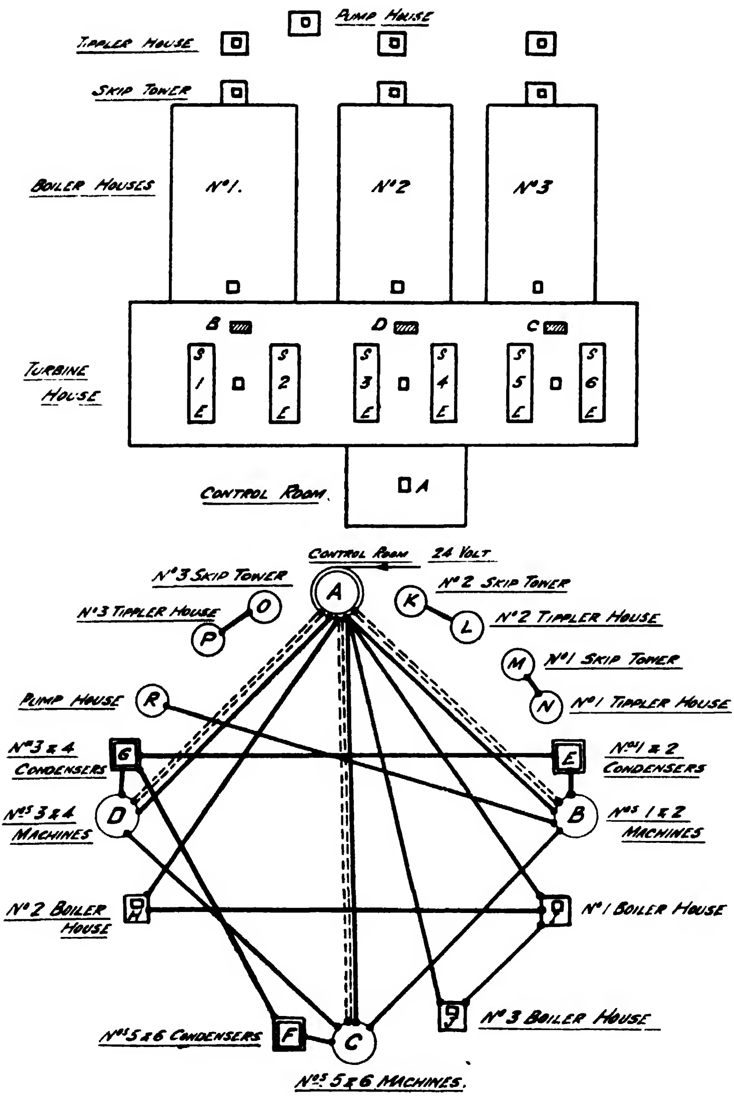


FIG. 457 Communication and Signalling Equipment.

Telephones and Telegraphs. The control engineer (through the charge engineer) is virtually the keeper of the station and is responsible for the receipt and transmission of all orders concerning its working. To enable him to issue instructions, telephones are

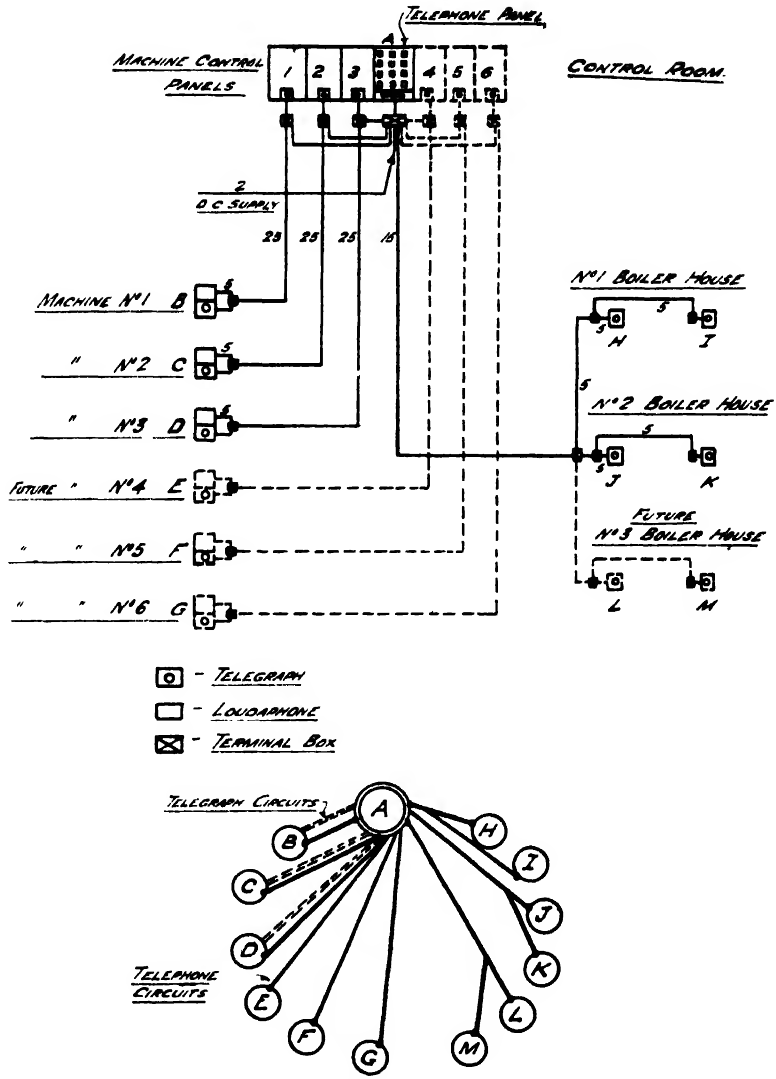


FIG. 458. Communication and Signalling Equipment.

provided at important sections of the station and telegraphs are necessary for transmitting orders to the turbine and boiler house superintendents or senior operatives. In this way he is able to transmit routine instructions concerning the running of the plant in a minimum of time.

For example, the control engineer should be in direct communication with the turbine drivers and leading boiler stokers ; the turbine drivers should be in touch with the turbine auxillary plant attendants and the leading boiler stokers and *vice-versâ*.

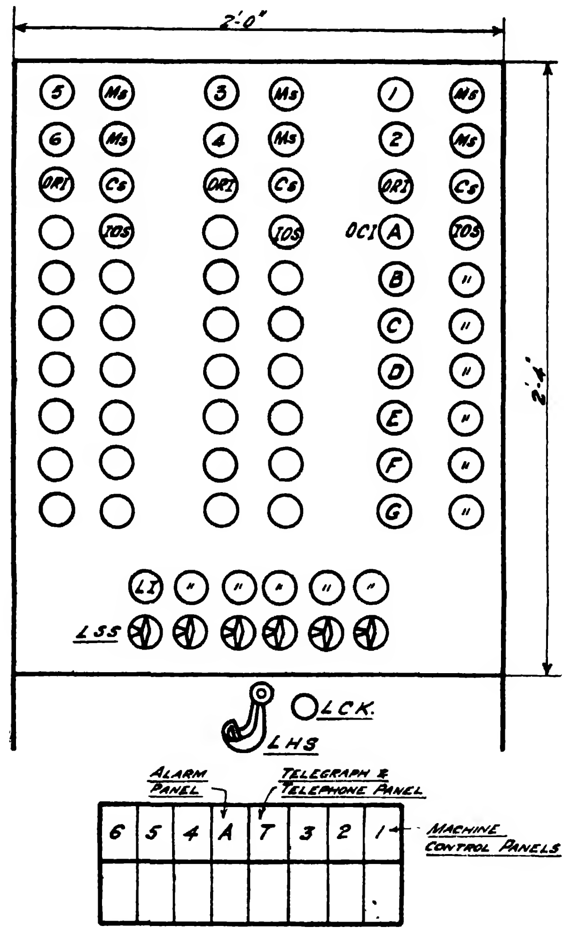


FIG. 459. Telegraph and Telephone Panel in Control Room.

In large stations it may be advisable for the turbine drivers to be in touch with each other, also the leading stokers in each boiler house. The coal-handling plant and pump-house attendants may also require telephone equipment. An efficient telephone system is

justified for even normal working, and more so for emergency conditions.

On a very large inter-connected system each station may be linked up to a central control room in which case the individual station control engineers would be responsible to the central control engineer.

The important distributing centres would also be under the supervision of the central control engineer. Some form of supervisory control may be used whereby the operation of important circuit-breakers throughout a system are indicated in a central control room. With the ever-increasing importance of electricity supply, a central control room is necessary for large inter-connected systems to deal with load distribution, voltage regulation, interruptions, breakdowns and the control of higher-voltage switching. The dispatch of electrical energy from the power stations and its control over many hundreds of miles of high-voltage mains is directed from this system control room through the medium of hundreds of substations. This control room is in direct communication with the primary substations by private telephone, supplemented by Post Office telephones and possibly wireless telephony. To control a large system from a central point the following equipment is necessary: system control diagram, telephones, metering and indication equipment, and supervisory control apparatus. The system diagram in the control room shows high voltage mains in distinctive colour for each voltage, substations and distribution centres as well as the operating position of the thousands of circuit-breakers at these places. Whatever scheme be adopted care should be taken to ensure its suitability for extension as the station increases in capacity, be simple and above all reliable. Some idea of the usual requirements will be obtained from Figs. 457 to 459. The inclusion of some form of interlocking switches will reduce the number of relays necessary.

The telephone and telegraph equipments mounted in the control room should be centralised as the operator then has all controls within easy reach. An alternative is to mount the telegraph transmitting units on the alternator control panels.

Telephones. The telephones should be of the heavy duty loud-speaking type in which the telephones themselves have a microphone incorporated that is sensitive only to nearby sounds. The undesirable background of noise prevalent in most parts of the station is to a large extent eliminated by use of this type. The

receiving portion of the telephone consists of a loud-speaking telephone and a loud-speaker, thus providing a "double sure" method of reception. Where the telephones are located in quiet positions the loud-speaker equipments may be excluded, *i.e.*, in the control room. Telephone circuit diagrams are shown in Figs. 460 to 462. The operation of a telephone circuit is as follows :—

A telephone selector switch is turned to the closed position, the telephone call-switch is then closed, which in turn lights the corresponding telephone indicator lamp on the control desk, the indicator lamp also operating a buzzer at the station selected.

The lifting of the telephone hand-piece from its rest automatically closes the speak switch.

Telegraphs. The orders to be sent from the control room to the turbine house for starting-up and running the turbo-alternators are

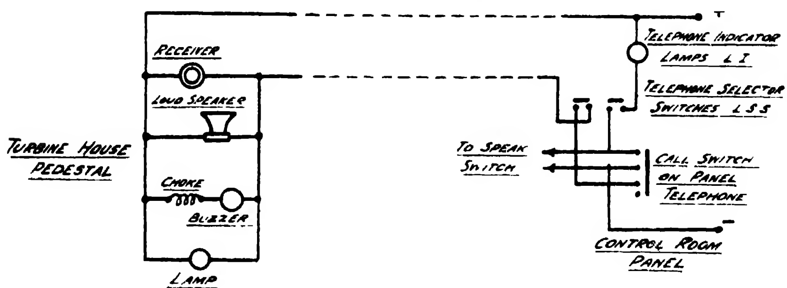


Fig. 460. Telephone Circuits.

conveyed by means of separate transmitters or alternatively a common transmitter. These are mounted on desk panels in the control room, and are indicated by luminous telegraph order indicators mounted near the steam ends of the machines.

An order indicator having a number of windows each of which cater for a pre-determined order, is adopted. The orders in the windows are normally invisible, but when a particular order is sent, a lamp circuit is energised, thus lighting up that order and making it visible.

The general practice is to mount the order indicator on a pedestal with the telephone equipment incorporated (Fig. 463). In some cases one order indicator serves two machines, this being very convenient when the steam ends are near. If this be used, some method of indicating the machine "called" must be provided. This may take the form of a beacon mounted on top of the pedestal which, when illuminated, would show the machine "called." The

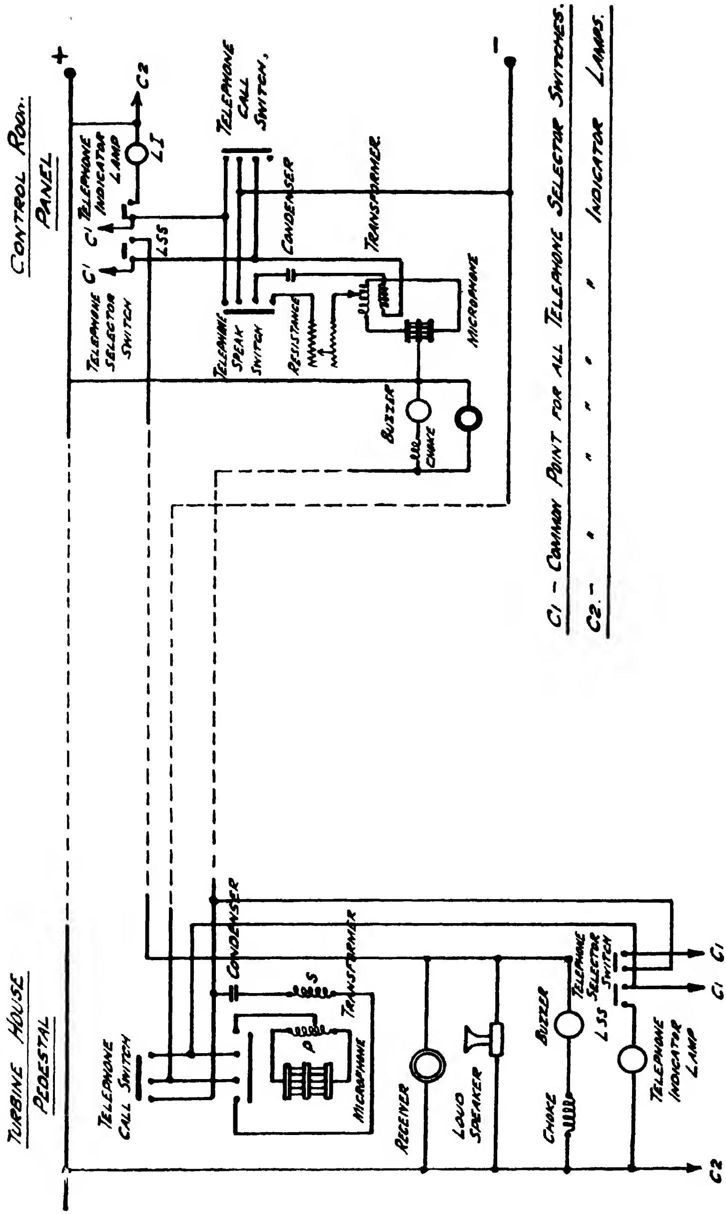


FIG. 461. Diagram of Connections for Telephone Equipment.

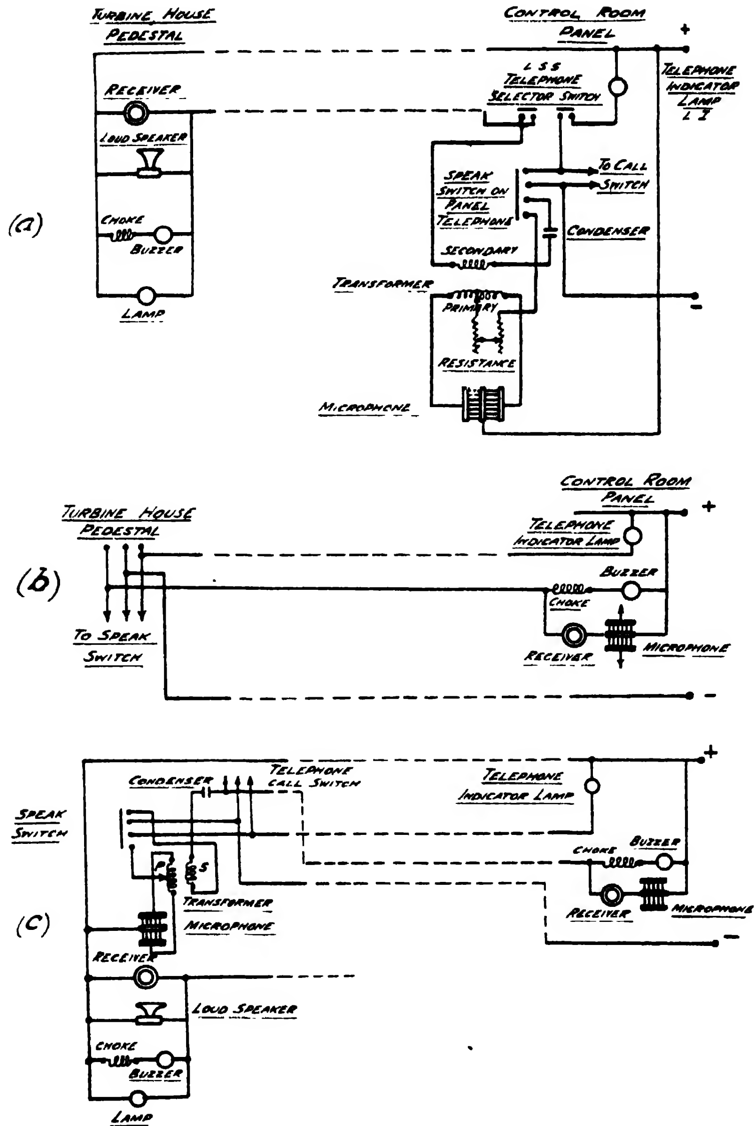


Fig. 462. Telephone Circuit Operations.

beacon may be dispensed with, and two additional smaller windows provided on the order indicator, these bearing the appropriate numbers of the two machines. To enable an attendant to observe

from a distance which pedestal has been "called," a large type of beacon may be mounted on a building column nearby.

A rectangular or triangular-shaped beacon indicator having one lamp of suitable wattage and fitted with small Morocco glasses

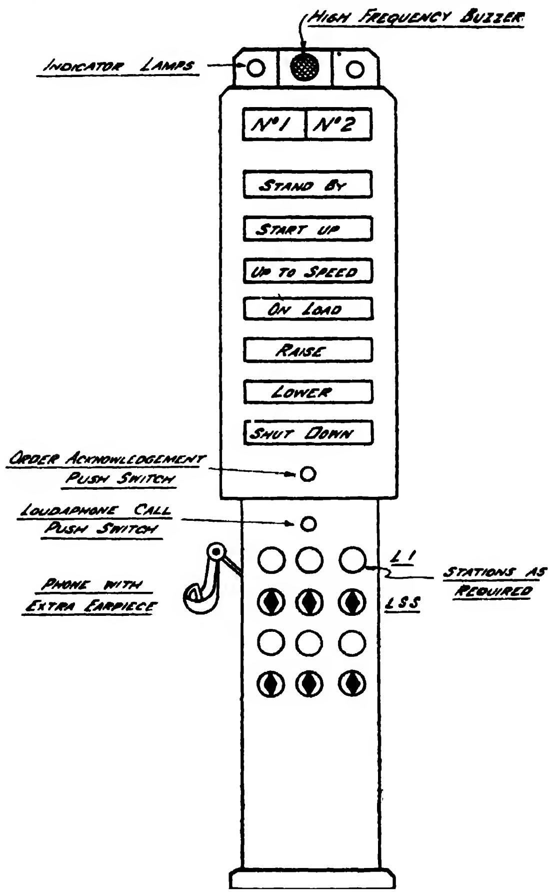


FIG. 463. Telegraph and Telephone Panel in Turbine House. (Clifford & Snell).

tinted light green is satisfactory. Each beacon would operate in conjunction with the call-up for the order indicator and telephone, the purpose being to indicate which pedestal is required. When the attendant reaches the pedestal he will observe which of the two machines is being signalled, or alternatively, which station is calling by telephone. A separate buzzer is recommended for each pedestal,

i.e., for two machines, which would provide for the audible call-up requirements of both telegraph and telephone at each pedestal. If only one buzzer be provided for the whole of the machines, there would be the danger of putting the turbine house communication system out of service should it fail. Although the pedestal type of order indicator has been almost universally adopted, it would appear that the telegraph and telephone equipments could be conveniently combined with the turbine gauge panel, and so make a central control point at the same time eliminating numerous small pieces of apparatus. A diagram of connections is shown in Fig. 464.

Staff Locator. This is a useful means of locating the staff and

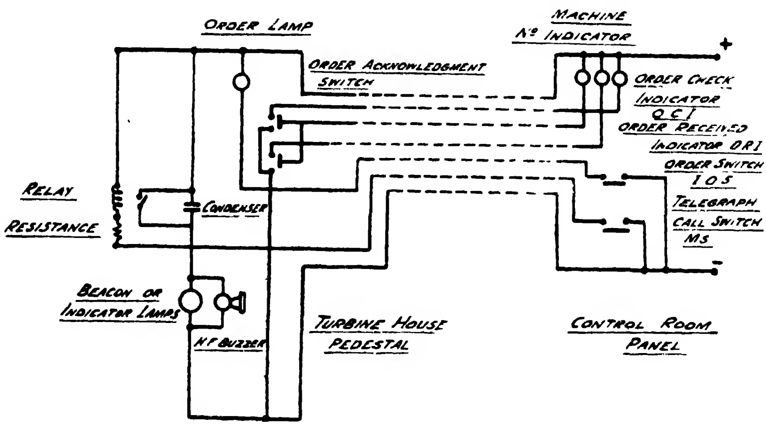


FIG. 464. Telegraph Circuits.

consists of a signalling transmitter which may be incorporated in the telephone desk in the control room and arranged to signal any senior member of the staff. The signal indicators would be mounted at a number of telephone stations throughout the various buildings. A flashing colour-light system appears to be quite effective, but if desired a simultaneous audible signal may also be added.

The operation of a typical system is generally as follows: the operator depresses the appropriate switch for the member required, this setting into motion a motor and cam mechanism which in turn " opens " and " closes " a number of mercury switches and causes the corresponding colour light to be flashed on the check indicator above the switch and at all signal indicator stations.

On observing the light the member required communicates with the control room engineer who then switches off the locator.

Load Indicator. Another type of indicator that is finding favour is for signalling the load in megawatts to each boiler house. The transmitter may be mounted on a desk in the control room and a large dial indicator placed in a convenient position in each boiler house. A summation wattmeter is sometimes used, but this only gives the load at any given time and although it enables the boiler house operatives to note any change in load, either rise or fall, it is not conducive to efficient combustion control to the full extent.

The ideal indicator would combine the features of the watt-

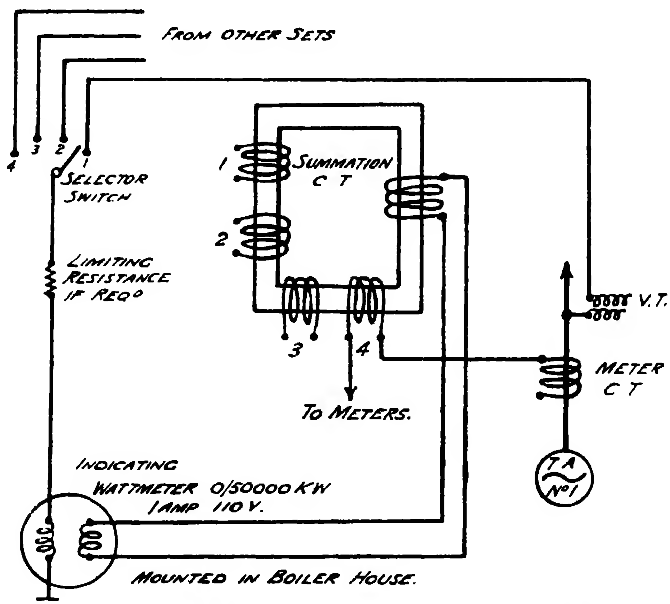


FIG. 465. Diagram of Connections for Load Indicator.

meter (variable) and the manual control (fixed) units. In this way the control engineer would signal the anticipated loading required whilst the wattmeter indication would show the immediate or present loading on the same dial. The load indicator has two pointers and the boiler operatives will maintain them as close together as operating conditions will permit. The practice in some very large stations is to have a central boiler house control room in which all the readings of the indicating instruments mounted on the boiler control panels are repeated on recording instruments.

Arrangements are made to transmit instructions to a central

panel in the control aisle or firing floor regarding the output required of each boiler.

This centralised "giant" boiler load indicator has two pointers for each boiler, which move up and down the scale of output. The red pointer is set by the control room, and the green pointer shows what output the boiler is actually giving. The boiler operative's duty is to keep the red and green together. The central control room is provided with a kilowatt meter, showing the total electrical

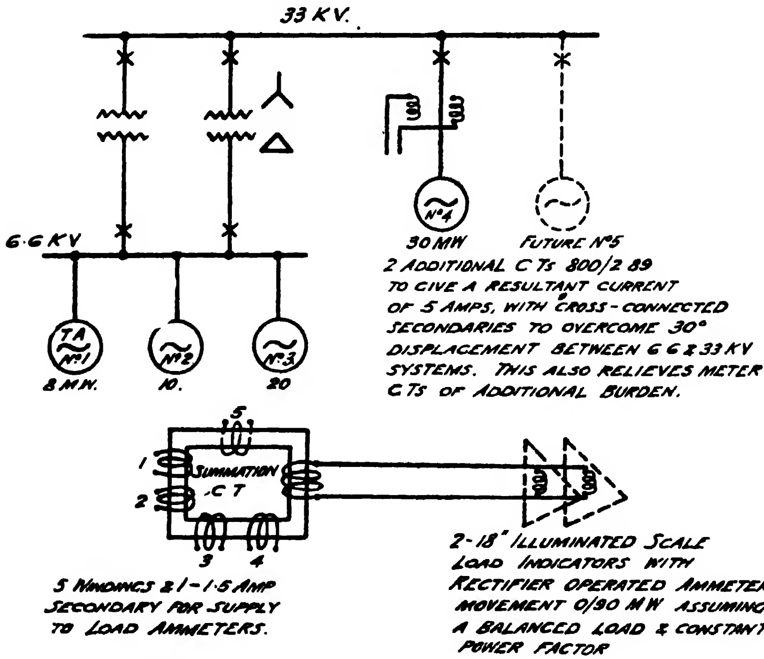


FIG. 466. Load Indicator Connections with Two Electrical Systems.

demand on the station, together with a master steam pressure gauge.

The Syncro Dial made by Clifford & Snell Ltd. enables advance indication of imminent load changes to be signalled to the boiler house immediately the station control room receives instructions from the central control room, so that firing adjustments can be made ahead of time. This is done by transmitting the "load direction" signal and obtaining acknowledgment, followed by rotating the handwheel control until the desired scale reading is obtained on the luminous indicator. A second pointer can be

provided when required to indicate "actual" load—being either manually or automatically operated as desired.

The advantages claimed for this equipment are :—

(1) A rapid and positive method of fore-signalling load changes to boiler house.

(2) An indication of actual summated load thereby enabling the boiler house operators to observe not only the amount of change in electrical load but subsequently the rate of change.

(3) The provision of (1) or (2) facilities singly or combined.

Load indicator connections are given in Figs. 465 and 466.

Synchronising Equipment. The synchronising apparatus may be either manual or automatic, but in general the former is usually adopted. The latter has been used in large capacity stations employing many small and medium output turbo-alternators for steam process work and electricity production.

The average time taken for one type of automatic apparatus to synchronise an alternator starting from the moment when the turbine is under the control of its governor, is thirty seconds. This is much in advance of manual operation, which is provided as a stand-by. The general principles concerning synchronising are well known, and the accompanying diagrams show the connection and apparatus included. The four conditions required to produce a state of synchronism are :—

(1) Running (bus-bar) and incoming set voltages should be the same.

(2) Frequency of the two supplies should be the same.

(3) Phase angle between the (running and incoming) two supplies should be zero—the two voltages are opposite.

(4) Phase rotation should be the same.

If the circuit-breaker of the incoming set can be closed when these conditions are satisfied, no undue disturbance will be produced. Although such ideal conditions are closely approached it can never be expected that these are always obtained in practice. The fact that A.C. machines can be synchronised satisfactorily and maintained in stable parallel operation is due to synchronising torques exerted when differences of frequency and phase angle occur.

When an incoming set has been paralleled the factors influencing the extent of any disturbance or surge which may arise are :—

(1) The capacity of running plant. (2) Moment of inertia. (3) Voltage difference. (4) Frequency difference. (5) Phase difference. (6) Synchronising torque.

An alternator can be synchronised satisfactorily with the scope moving in either the "slow" or "fast" directions. Both methods are followed in practice and can be considered correct. The advantage of synchronising the incoming set "fast" is that it will automatically pick up a small load. The incoming set should be switched on to the busbars just before it reaches instantaneous synchronism and while it is ahead of the running sets. It then drops smoothly into phase as it takes up load. The advantage of bringing the incoming set on to the bars in the "slow" direction is that it will more or less "trail in," and this is a useful feature when the steam

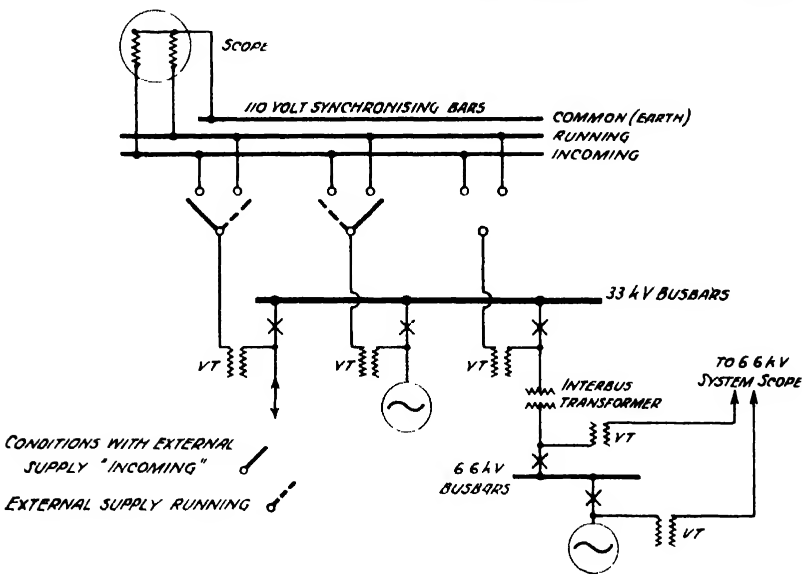


FIG. 467. Synchronising Connections.

pressure is very low. If a reverse power relay is fitted it will trip when the alternator is synchronised slow for the alternator will be motoring, *i.e.*, taking power.

The frequency error, when paralleling, should be kept as small as possible, thereby obtaining a creeping speed of the scope pointer. It has been suggested that the frequency difference should be kept below 0·1 per cent. For a given percentage frequency error, less danger of surging or disturbance will obtain if synchronising is carried out late rather than early. The scope pointer rotates at a speed proportional to the difference in the two frequencies. The pointer is capable of continuous rotation round the dial and rotates

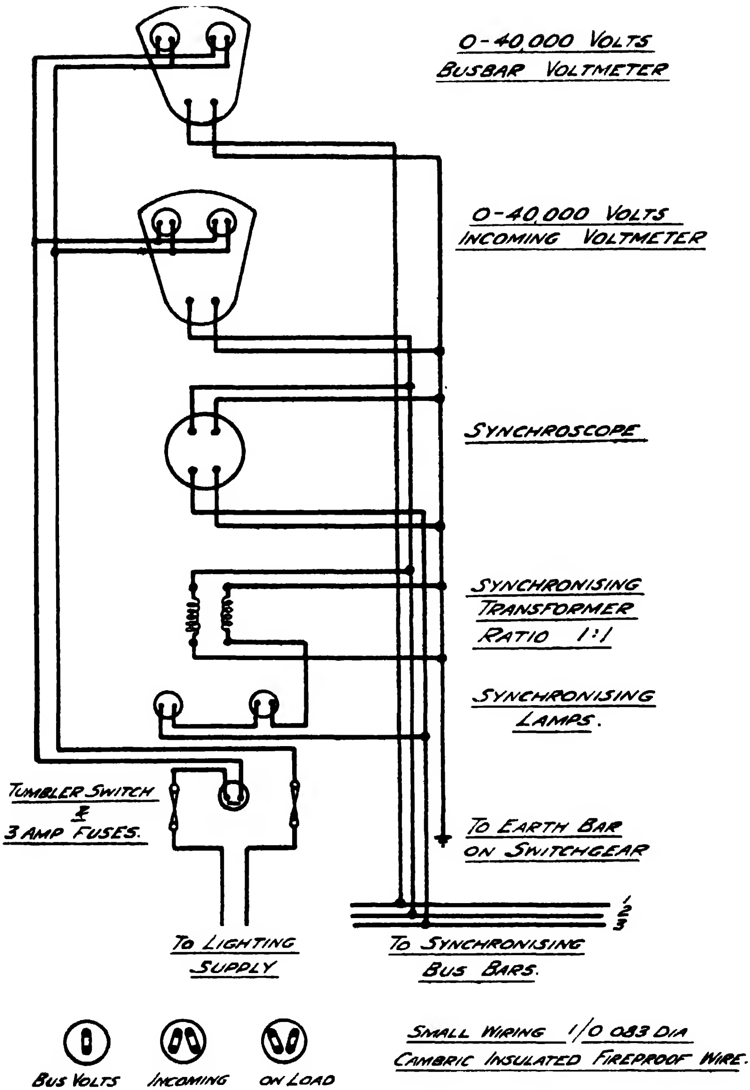


FIG. 468. Synchronising Frame Connections.

clockwise when the incoming set is too fast and counter-clockwise when the set is running slow. Synchronism is attained when the pointer remains stationary at the twelve o'clock position. In the actual process of synchronising, the speed of the incoming set is

adjusted until the pointer of the scope is rotating very slowly, probably 2 or 3 r.p.m., in direction marked " fast " if load is to be picked up immediately.

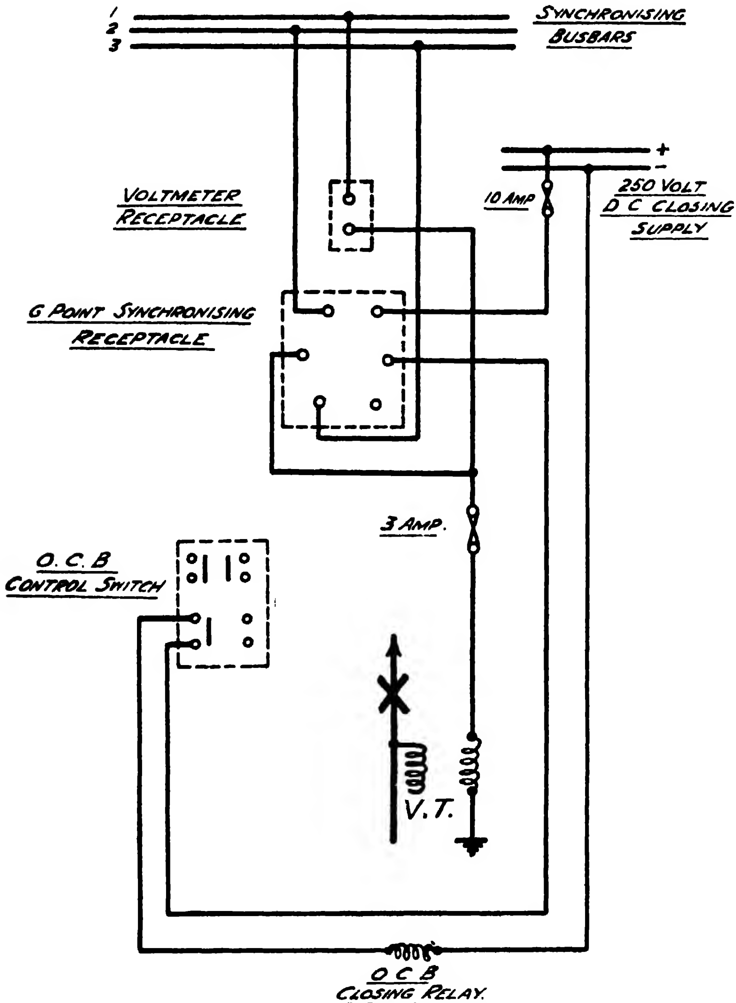


FIG. 469. Control Panel Synchronising Connections.

The speed of the incoming set is adjusted by means of the governor motor drive or alternatively by the turbine driver if such remote control is not provided. If the interconnected system frequency is low and beyond the governor then the speed of incoming

set can be controlled by the turbine stop valve. Then, after adjusting the voltage of the incoming set to that of the busbars the circuit-breaker is closed first as the pointer is coming to the vertical position. In addition to equality of frequency the voltage of the incoming set must also be in phase with that of the busbars. This is indicated on the scope by the pointer being vertical. If the pointer is in any other position the voltages are out of phase, deflection of the pointer from the vertical being an indication of phase difference. The consumption is about 12 VA for each circuit and the rating is such that an instrument should not be left in circuit for more than 15 to 20 minutes. The voltage transformers can be arranged for synchronising between any two phases, *i.e.*, blue and yellow, red and yellow, etc.

The interconnection of stations requires adjustments to be made at the incoming station to effect parallel operation. Assume the incoming supply to be fast (*i.e.*, incomer fast), then the scope pointer rotates in a clockwise direction (*i.e.*, fast), and as there is no control from the incoming stations it is necessary to readjust operating conditions of the local station sets. The governors are placed into the "raised" position and so increase the steam input with consequent increase in speed and frequency. The reverse procedure would be adopted if the incoming supply was slow. Fig. 467 illustrates typical connections.

A special swing frame or panel accommodates the instruments and lamps. The number of synchronising equipments required will depend on the switchgear layout and the number of voltages obtaining in the station. Two synchronising pedestals are quite common and are placed in front of the alternator control board. Each pedestal has a synchroscope, synchronising lamps and two or three large sector type illuminated dial voltmeters, indicating respectively alternator volts, incoming machine volts and probably feeder volts. Typical diagrams of connections are given in Figs. 468 and 469. Portable synchronising equipments are also used.

Metering Equipment. The metering equipment for individual alternators and feeders is mounted on the associated control or relay panels. If the station is inter-connected with other stations and exports or imports power, then it may be necessary to provide additional metering equipment. The feeders arranged for the export and import of power have metering equipments with arrangements for change-over from export to import or *vice versâ* as desired. Where stations operate under the direction and control

of an outside authority, this authority may install additional metering equipment for each alternator, and also summation metering for the station. A typical equipment is shown in Figs.

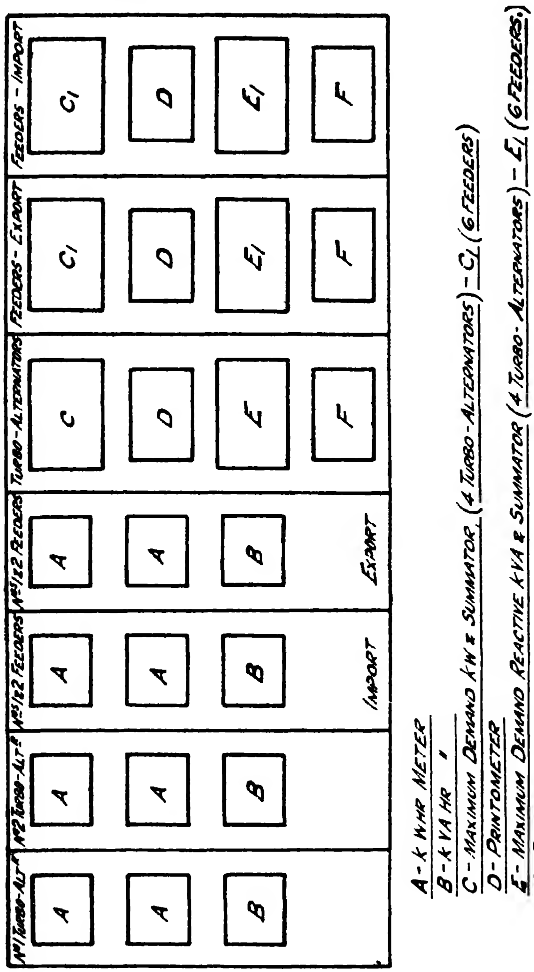


Fig. 470. Typical Metering Equipment Panels.

470 and 471. This additional metering equipment may be placed in the control room or in an adjoining room.

Under certain conditions of operation, e.g., with no alternators in commission it is possible to export kVAr. This is possible where the high voltage cables act as a capacitor and generate lagging kVAr which is recorded on the kVAr export meter.

Frequency Control. With an isolated station frequency control is fairly easy, since the operating staff know the load conditions and can make the desired adjustments from time to time. The inter-

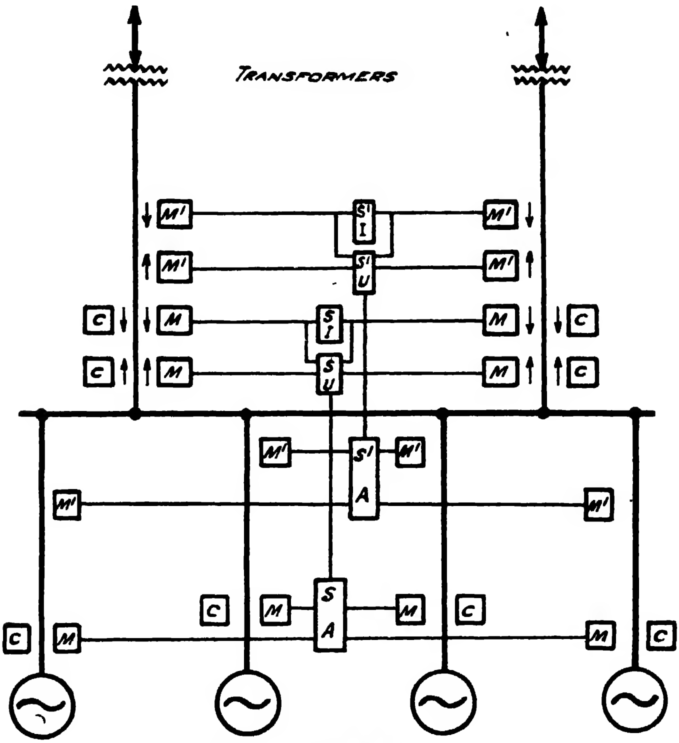


FIG. 471. Typical Metering Arrangement.

C—Integrating check meter kWh.
M—Integrating main meter kWh with summating attachment kWh.
M^1—Integrating main meter with summating attachment reactive kVA.
SA—Alternator summator kW.
S^1A—Alternator summator reactive kVA.
SU—Undertaking summator demand kW
S^1U—Undertaking summator demand reactive kVA.
SI—Import summator demand kW.
S^1I—Import summator demand reactive kVA.

connection of large stations brings into being a central control or load-despatching unit from which all plant on the system is controlled. It is a question of parallel operation of turbo-alternators and the greater the frequency variation the more regulating all stations have to do, because of the difference in governor char-

acteristics. If a large station with fine governor setting operates in parallel with a smaller one having coarse governing the major part of any load increase is taken by the larger station. The present method of operation allots definite output schedules to every station but one which regulates its output so as to maintain the system frequency constant. Some of the chief causes of variation in frequency are :—

(1) Variation in steam pressure at turbine stop valve.
(2) Variation in recognised load.
(3) Faults and defects on plant.
(4) Incorrect adjustment of turbo-alternator outputs.

The growth of load, in magnitude and diversity, and the interconnection of large undertakings tend to reduce the importance of causes (1), (2) and (3), but render much more difficult the avoidance of cause (4).

Assuming the governor on the 90 per cent. setting, the machine will carry 90 per cent. load at a frequency of 50 cycles per second. With the governor on the same setting the machine will carry more load at a lower frequency or less load at a higher frequency. In order to carry more load or less load without change of frequency it is necessary to raise or lower the governor setting respectively. Frequency control or regulation has an important bearing on many problems which confront the electrical engineer some of which are :—

(1) Generating efficiency and speed of station auxiliaries. This effect always tends to increase frequency errors.

(2) Alternator excitation, particularly when not automatically regulated.

(3) Power factor of induction motors, performance of power factor improvement plant, and the magnitude of line capacitive currents.

(4) The speed of industrial motors with its effect on consumers' maximum demand.

(5) The effect on electric clocks which are now widely used on networks.

To enable clocks to be operated from the electricity-supply it is essential to control the generated frequency to within very fine limits in relation to standard time. A device is provided in which an electric motor-driven clock supplied from the station frequency is compared with a standard clock, the pointers of both clocks appearing on the same dial. Both pointers are driven by the same electric motor, but the pointer indicating standard time is connected to the spindle of the motor by a friction-clutch and its position is checked every thirty seconds by electrical impulses from a standard pendulum. If at any moment its position does not correspond to

standard time, then the impulse checking device moves it round on the friction-clutch to the correct position. The speed of the alternators, and hence the frequency, is adjusted so that the two pointers remain as near as possible coincident.

Although most of the principal stations in the supply area will have such a device, it is almost impossible for a number of interconnected stations to control their frequencies separately, and the duty of regulating the frequency of the system is allotted to one station. Various methods are used to control the frequency of a system comprising a large number of stations operating in parallel. The method adopted depends primarily on the plant, amount of load rise in the morning and fall in the evening, also the load variation during the day, apart from the mid-day period. If the system frequency falls to 48 cycles (50 cycles normal) and is still falling, or if the load on transmission equipment rises to 50 per cent. overload and shows no sign of falling, immediate action is taken by the control engineer to drop load on the distribution system to restore stable conditions. Load shedding is carried out by the power station staffs on receipt of instructions to do so from the system control engineer.

Load Flow Calculator. The object of this calculator is to give, in the simplest possible manner, the magnitude and direction of the load flowing in any of the main transmission circuits under predetermined conditions of loading at various power stations and bulk supply stations on a network. Further, it can be used to study the effect on circuit and plant outages once it has been set up to represent a particular condition. Fixed resistances are used to represent the electrical characteristics of each network circuit, whilst the import or export at each supply point is fed into the network by plug-in resistances connected to the supply. Any required switching conditions can be set up by means of plugs fitting into plug-block units. To read the load flowing in any circuit, the appropriate plug is replaced by a split plug in series with a milliammeter which slides on a carriage in front of the calculator. It operates on 100 volts D.C. and by means of a universal unit which can be hinged to either end of the main calculator and connected by flexible leads development problems involving projected extensions of circuits and stations can be set up and investigated.

Batteries and Motor Generators. With electrical operation of all main switchgear it is essential to provide at least one battery, but in large stations two batteries are usually installed. In some

stations a number of direct current auxiliaries are still favoured and if the outputs are of the order of 100 H.P. and over, a special medium-voltage large-capacity battery may be installed as standby to the normal direct current which may be supplied by motor generators, motor converters, rotary converters or rectifiers. In the early smaller stations a battery served the following purposes :—

(1) Assistance in dealing with storm loads.
(2) Standby to converting plant.
(3) Standby to boiler plant.
(4) Load equalising enabled output of generating plant to be kept more constant.
(5) Inferior coal may affect steam conditions.
(6) Ensuring continuity of supply generally.

Where direct current is only required for switchgear closing and tripping, emergency lighting and small auxiliaries, the capacity of the battery will be determined by an assumed proportion of switch units closing simultaneously. Direct current may also be used to excite the fields of the direct coupled exciters or in case of exciter failure supply the alternator field system.

When two batteries are provided arrangements may be made to carry the load with one while the other is being charged. Sometimes one battery is arranged to take over automatically the supply to the emergency lighting, and also to supply the switchgear closing circuits. The other will supply energy for indicating lamps, tripping circuits and any small direct current power that may be required, such as exciter field rheostat control, governor control, valve and damper controls. Where only one battery is installed and there is no alternative supply during charging periods the charging generator circuit-breaker is arranged to trip out in order to avoid burning out of lamps, etc., due to the higher charging voltage on changing over from normal A.C. to emergency D.C. lighting. The inclusion of trickle-charging apparatus is finding favour, and is frequently met with in battery installations (Fig. 472). Trickle-charging is a method by which a battery already in a fully-charged condition may be maintained indefinitely in that condition without deterioration and without the necessity of giving periodical charges and discharges. The maintenance of a fully-charged battery is ensured by passing a very small current continuously, the current being just sufficient to balance the losses which occur when a battery is on open circuit. Insufficient charge is responsible for rapid deterioration of the plates. It is also claimed that a battery with

trickle-charging equipment may be placed in a room where metal work is unprotected for there is no acid gas given off and no corrosion, and a longer life is obtained. When alternating current is available a rectifier will be necessary, but in the case of direct current, resistances will serve to limit the current as required. The batteries should be placed near the main control circuits and if possible in

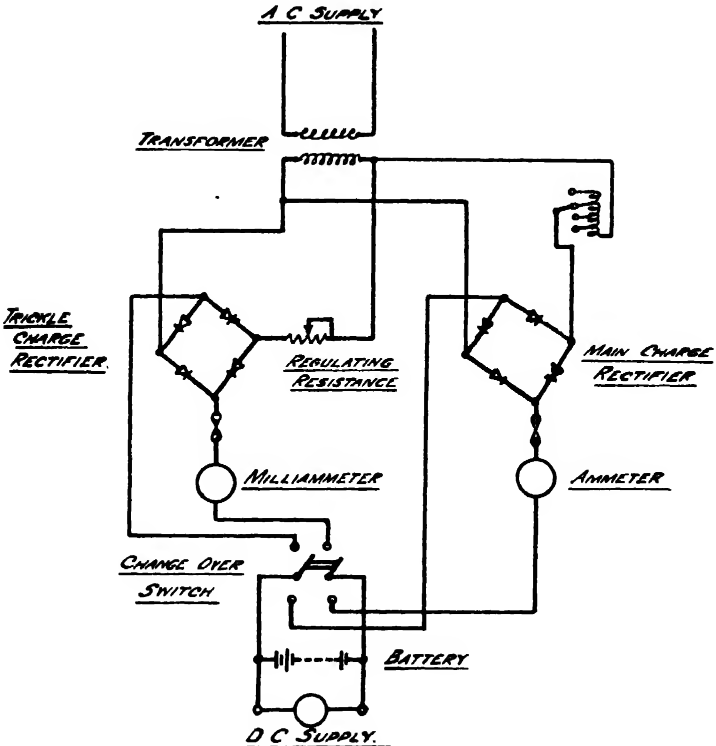


Fig. 472. Trickle Charging Circuit.

the vicinity of the control room. Where batteries of large capacity are installed it is preferable to house them at ground level to facilitate handling. If this cannot be arranged and a room directly above some other equipment is the only alternative, it is advisable to raise above floor level all doors and other openings into the battery room. A liquid-tight well is thus formed which is able to retain the whole of the acid contained in the battery should there be a serious failure.

The room should be of sufficient size to permit of easy access for inspection and maintenance of every cell. A plain concrete

floor will in most cases be quite satisfactory provided the necessary care is taken in swilling off any acid. The concrete may be covered with a layer of acid-resisting asphalte or treated with silicate of soda. A coating of wax prevents wear and consequent dust. The floor should be levelled and provided with channels for drainage where considered advisable. To minimise corrosion it may be necessary to treat all wood and steelwork with acid-proof paint and enamel. The copper conductors may also require treating in a similar manner. Where provision is made for restricting gas formation and evaporation it may not be essential to adopt these precautions. Evaporation may be prevented by covering the acid level of each cell with a thin film of oil. There should be adequate ventilation in the form of air bricks and louvres or an exhaust fan, although the risk of an explosion is very remote. In some cases it may be necessary to install an acid neutraliser to render the fumes discharged from the battery rooms free from acid and incapable of causing corrosion of any steelwork, etc., in the vicinity of the discharge from the rooms. A motor-driven fan, pipework and water supply to the neutralisers will be necessary.

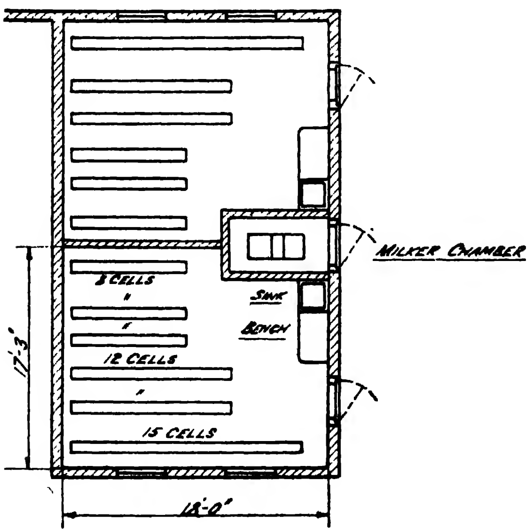


FIG. 473. Layout of Battery Rooms.

A reasonable amount of natural and artificial lighting is desirable.

A water supply together with sink, bench, etc., should be installed in each room (Fig. 473) to enable flushing, cleaning and general overhaul to be carried out. The acid and distilled water carboys may be placed in some convenient positions in the battery rooms. The connections between the various sections of the battery and the switchboards are usually bare copper rod or strip which should be maintained rigid and at least 8 ft. above any access platform to prevent accidental contact.

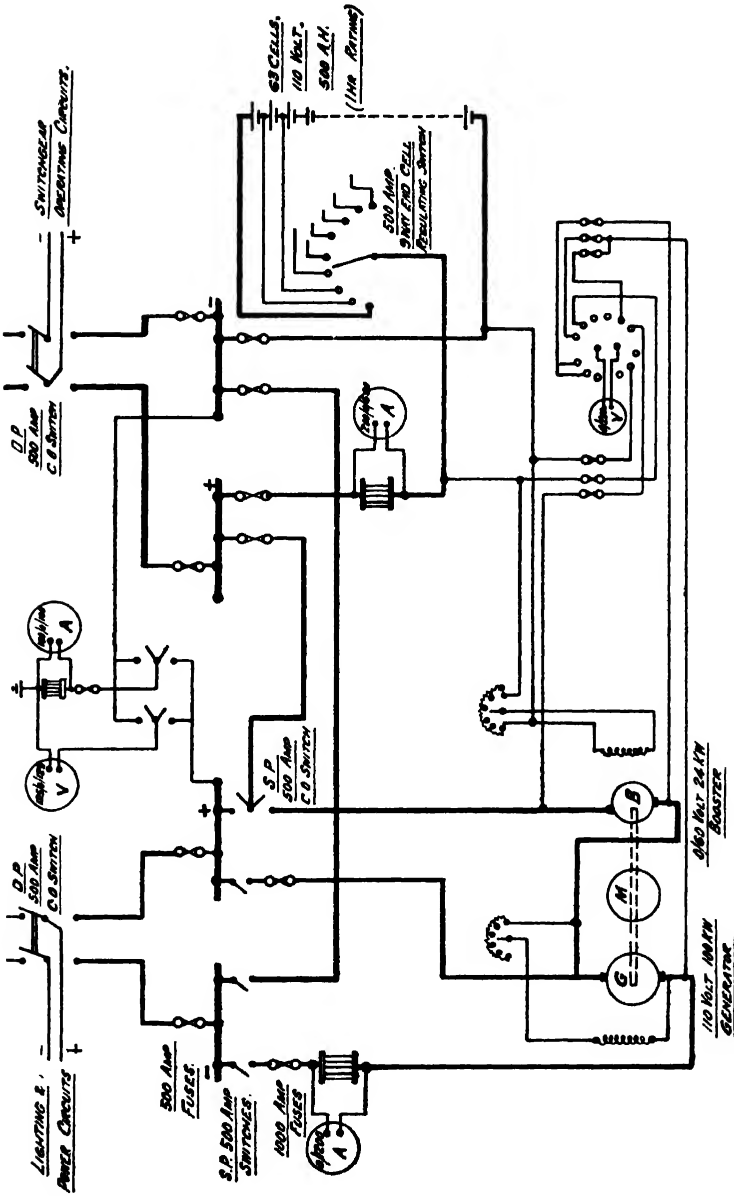


FIG. 474. Motor Generator and Battery Equipment

The batteries are charged by motor-generator-booster sets, Figs. 474 and 475, which may also be used to maintain the bus-bar voltage at normal value during charging periods and at times when the batteries are disconnected.

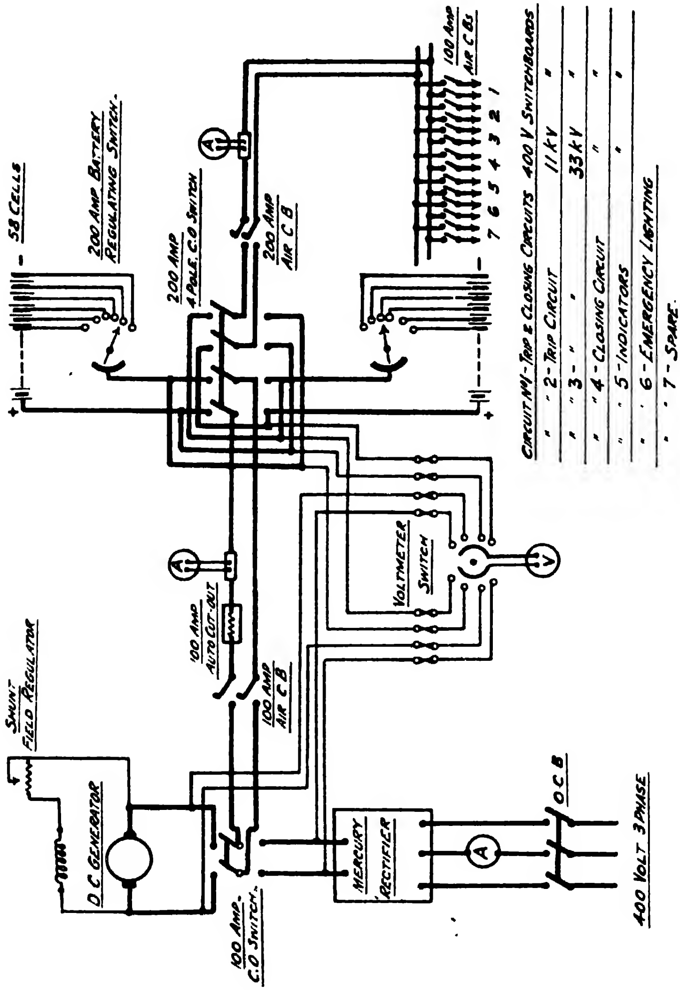


Fig. 475. Battery Charging Equipment and Main D.C. Circuits.

The booster is necessary to augment the generator voltage during charging periods. In some installations the generator is arranged to deal with charging, and in this case a booster is not required.

The only type of manually controlled booster in general use is the charging or shunt booster which raises the generator voltage

when charging a battery, the latter being arranged to carry the entire load alone or be discharged in parallel with the generator and assist at peak load.

When charging is commenced the booster voltage is very low and the excitation weak but the charging current may be very large. With such a condition it is possible for the resulting armature reaction to cause reversal of polarity and to overcome this difficulty the booster is arranged for separate excitation. In some cases a reversible booster motor-generator equipment is installed. To enable any cell to be charged a small motor-generator set or milker (Fig. 476) may be included. This may be placed in the main motor-generator room or in a separate chamber near the battery rooms. It is usual to arrange for two bare copper bus-bars to run round the

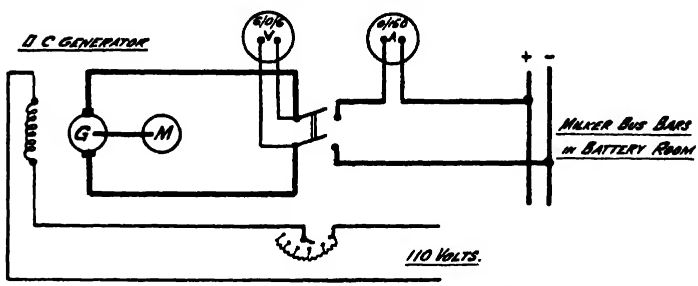


FIG. 476. Battery Milker Booster.

battery rooms and provide two insulated leads with clips and connectors to enable any cell to be connected for charging.

The motor-generator-booster sets should always be kept away from the batteries and a room adjoining or immediately above the battery rooms is satisfactory providing the ingress of acid fumes is prevented. The switchboards for each set may be accommodated in the motor-generator room and if possible arranged to permit of easy connection to the end regulating cells. A convenient method of leading in these connections is to group them and in course of construction leave a slot in the floor or wall of sufficient size for them to pass through at suitable centres. A slate or concrete slab having the necessary number and sizes of holes may then be placed in position and the bare copper connections sealed and the slab cemented up. The switchboards are usually of the flat-back type, the panels being of slate upon which are mounted the air break switches, circuit breakers, fuses and instruments. The backs of the boards should be screened to prevent unauthorised access. In view of

their importance and where convenient the D.C. control boards are sometimes placed in the control room. A typical motor-generator battery installation is outlined for a 110-volt system, each battery having a discharge capacity of 500 amperes for one hour.

In estimating the requirements of the various systems reference should be made to data compiled by leading battery manufacturers.

From manufacturers' data (Chloride Electrical Storage Co. Ltd.) :—

1,000	ampere-hours in	10 hours	to	1·85 volts per cell.
833	,, ,,	5 ,,	,,	1·82 ,, ,, ,,
500	,, ,,	1 hour	,,	1·75 ,, ,, ,,

Normal charging rate . . . 138 amperes.
Maximum ,, ,, . . . 277 ,,

The number of cells in battery is given by :—

$$\frac{\text{Minimum line voltage permissible at end of heaviest discharge}}{\text{Final voltage per cell when on heaviest discharge}} =$$

$$\frac{110}{1 \cdot 75} = 63 \text{ cells.}$$

This figure includes the regulating cells.

The number of regulating cells is given by :—

$$\text{Number of cells in battery} - \frac{\text{circuit volts}}{2 \cdot 1}$$

$$= 63 - \frac{110}{2 \cdot 1} = 8 \text{ cells.} \quad \left(\text{Open circuit voltage is taken as } 2 \cdot 1 \text{ volts per cell.}\right)$$

A booster is to be incorporated in the equipment the output of which is to be equal to the rate of charge of the battery, and its maximum voltage equal to the difference between that required to charge the battery and the normal circuit voltage.

$$\begin{aligned} &\text{Charging voltage per cell} = 2 \cdot 75 \text{ volts.} \\ \therefore\ &\text{Battery charging voltage} = 2 \cdot 75 \times 63 \\ &\qquad = 173 \text{ volts.} \\ &\text{Normal circuit voltage} = 110 \text{ volts.} \\ \therefore\ &\text{Booster voltage} = 173 - 110 \\ &\qquad = 63 \text{ volts.} \end{aligned}$$

As a check, the booster should be capable of giving at least the normal charge continuously at a voltage of :—

$$\begin{aligned} &\text{Circuit volts} - (\text{total number of cells} \times 2 \cdot 3) \\ &= 110 - 63 \times 2 \cdot 3 \\ &= 65 \text{ volts.} \end{aligned}$$

$$\text{At normal charge the booster capacity} = \frac{138 \times 65}{1{,}000}$$
$$= 9 \text{ kW.}$$
$$\text{At maximum ,, ,, ,, ,,} = \frac{277 \times 65}{100}$$
$$= 18 \text{ kW.}$$

The booster should be arranged for separate excitation from the D.C. generator and have a rated output of 400 amperes with an overload capacity of 500 amperes for two hours, the voltage being adjustable from zero to 60 volts at any current between nothing and 500 amperes.

By adopting a high output the booster would be safeguarded against possibility of damage if it had to carry maximum current.

$$\text{The booster capacity in this case would be} = \frac{400 \times 60}{1{,}000}$$
$$= 24 \text{ kW.}$$

To determine the output of the generator it is necessary to know the approximate total D.C. load for the station. A reasonable margin should always be allowed.

For a 300-MW station there may be anything up to 1,000 amps. at 110 volts, this would include emergency lighting, switchgear and motor control. Assuming a maximum load of 1,000 amps., there would be two batteries each having a discharge capacity of 500 amps. for 1 hour. It may be advisable to design the two motor-generator sets to be each capable of dealing with the total station load, one always being reserved as standby. In this case the total load $= \frac{1{,}000 \times 110}{1{,}000} = 110$ k.W.

The output of the driving motor = booster output + total load.
= 24 + 110
= 134 kW. or = 180 H.P.

A summary of the necessary equipment is appended.

Battery :

Discharge capacity . 500 amps. for 1 hour.
Number of cells . . 63, including 8 regulating cells.

The cells should be of the lead-lined wood type arranged for erection in a single tier and be supported on insulators erected on wooden

stands, the bottoms of which should be at least 1 ft. from the floor. The stands should be painted with acid-resisting paint or enamel. An end-cell regulating switch should be provided and arranged to regulate a number of cells in steps of two.

The equipment should include acid, hydrometers, thermometers, inspection lamp, cell-testing voltmeter and all other accessories.

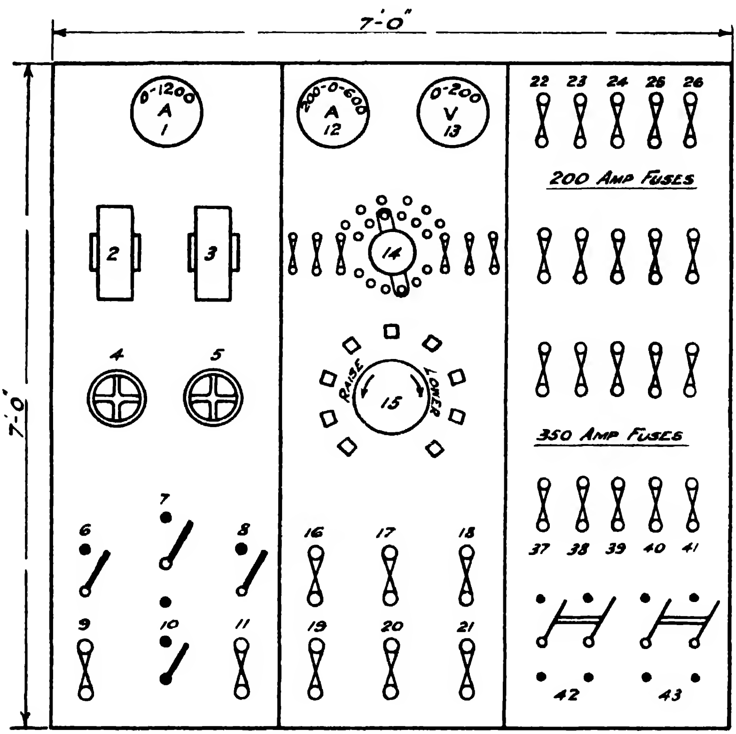


FIG. 477. Typical Generator and Battery Switchboard.

1—Generator amps.
2—Generator fuse + ve.
3—Generator fuse — ve.
4—Generator voltage rheostat.
5—Booster voltage rheostat.
6—Generator isolator + ve.
7—Battery isolator + ve.
8—Generator isolator — ve.
9—Emergency lighting fuse + ve.
10—Battery isolator — ve.
11—Emergency lighting fuse — ve.
12—Battery amps.
13—Voltmeter.
14—Voltmeter switch.
15—Battery switch.
16—Switchgear operating + ve.
17—Battery + ve.
18—Generator + ve.
19—Switchgear operation — ve.
20—Battery — ve.
21—Generator — ve.
22–26—Main switchgear closing circuits.
37 & 38—Main switchgear tripping.
39 & 40—Auxiliary switchgear tripping and closing.
41—Power company's tripping and closing.
42 & 43—Change-over switches.

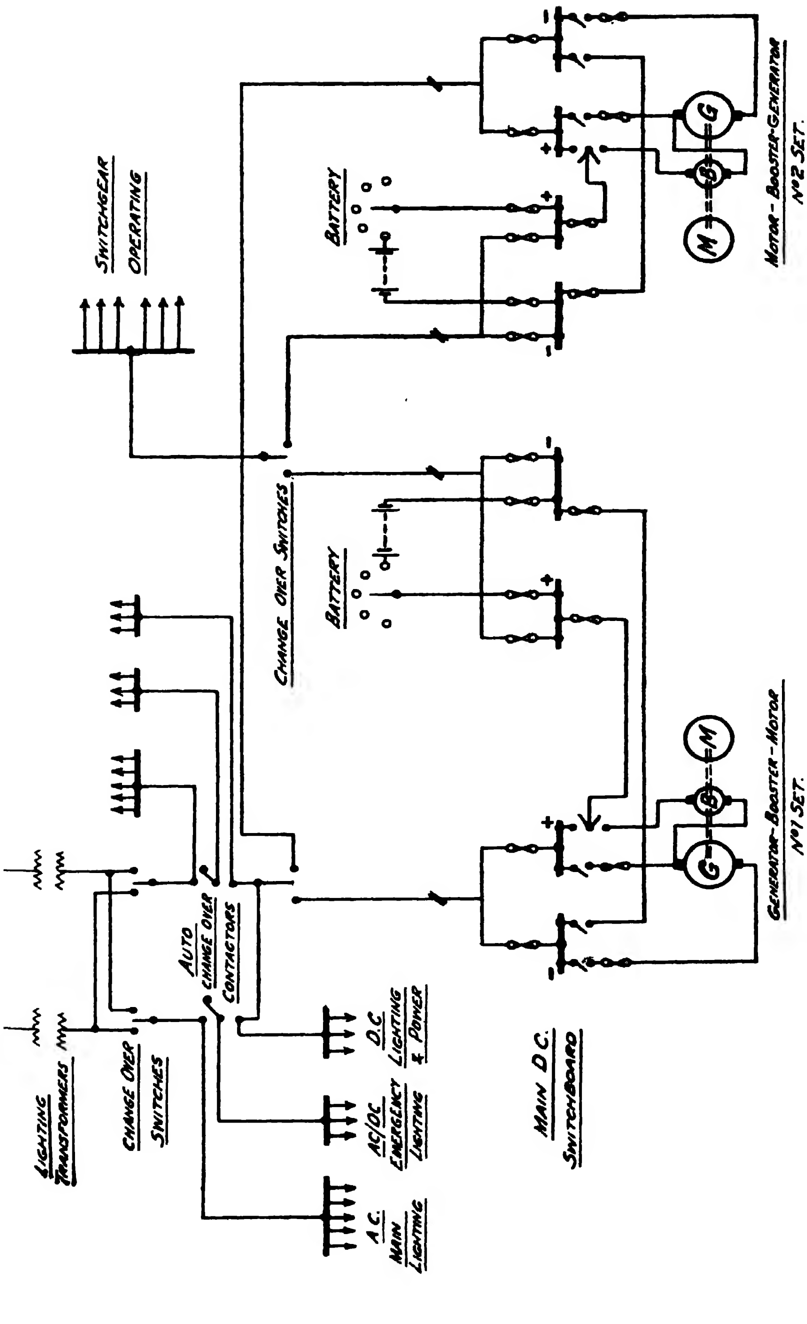


FIG 478. Diagram of Main D.C. Circuits.

Generator :

Four-pole shunt wound interpole.
Output : 100 k.W., 1,000 amps., 100–120 volts.

Booster :

Four-pole shunt wound interpole.
Arranged for separate excitation from generator.
Output : 24 k.W., 0–60 volts.

Motor :

Squirrel cage, 3-phase, 400 volts.
Output : 190 B.H.P., 730 r.p.m.

Milker :

Two-pole shunt wound.
Arranged for separate excitation from 110-volt supply.
Output : 120 amps., 2–6 volts.
Driven by 3-phase, 400-volt squirrel cage motor.

The usual controlling switchgear, instruments, field rheostats, etc., should be included.

The equipment generally supplied is shown in Figs. 477 to 479.

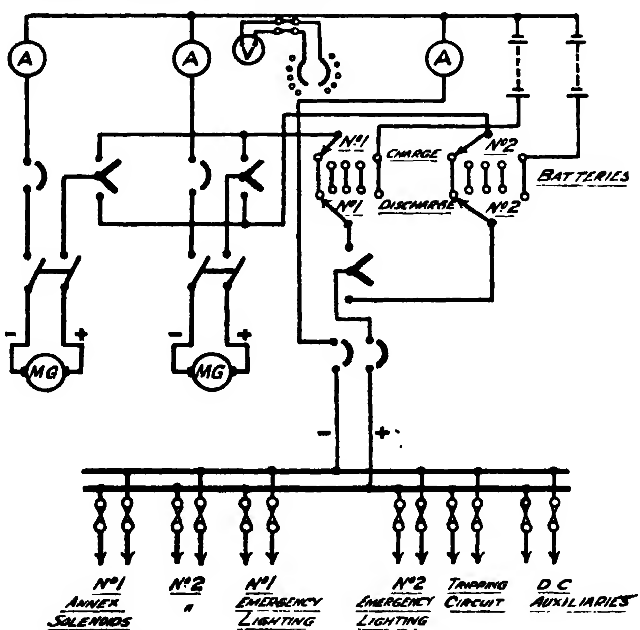


FIG. 479. Diagram of Main D.C. Circuits.

Earth Fault Indicators. Earth-fault indicating lamps or detector equipment may be included. If lamps are used they may pass sufficient current to operate certain sensitive relays (alarms, etc.) and so produce an earthed system. A sensitive earth leakage alarm may be arranged to give warning should the insulation resistance fall to 20,000 ohms. Some switchboard relays operate at 10 mA. and with a single earth a relay has been operated by the leakage current of the earth detector. To retain the advantages of continuous leakage detection and of an insulated system a minimum current for any relay is specified at 50 mA. minimum.

Control Room Organisation. The first consideration in the operation of an electrical system whether it be small or large is continuity of supply.

The organisation should be such that the control engineers—both station and system—are immediately informed of any abnormal operating conditions and they should be thoroughly conversant with the rated capacity of the plant available and standby at each station, the exact loading conditions of the system, the network demands, the rating and loading of all plant including lines and interbusbar transformers, and the types of protection in use. They should also maintain close touch with all happenings on the system, especially where men are working on high voltage apparatus. A control or operating engineer is generally responsible for the following during his shift :—

(1) All switching.

(2) Regulation of voltage, frequency and power factor and maintenance of continuity of supply. The station control engineer is under the direct supervision of the shift charge engineer.

(3) The transmission and distribution of electrical load at each point on the system and between the various power stations.

(4) The number of alternators on load, available and standby, at each power station and the regulation of load on individual sets so as to obtain maximum operating efficiency.

(5) Keeping a record of all switching, linking and earthing carried out with the times of the operations and the names of the operators.

(6) Recording of half hourly loadings at each station and on important feeders.

(7) Recording weather conditions and taking routine precautions necessary to safeguard supplies.

Other duties may be added which vary according to circumstances and local conditions.

CHAPTER XV

CABLING AND CABLES

THE concentration of large units in stations has introduced special problems associated with the design of cable runs and this applies to all cables, from multicore control to high-voltage main cables. Cables are one of the most important links in the chain of electricity supply, therefore the types to be used for the many and varied services should be chosen to comply in all respects with the conditions likely to be met. The power station has also to provide for the outgoing feeder cables, and in a large station these may number fifty or even more, a great deal depending on the area served, transmission voltage and local conditions. With the advent of high-voltage alternators, 20 to 36 kV., main cabling has been simplified as the number of cables required per phase are reduced (Table 59 and Fig. 480).

The installation of cables is also important and special attention should be given to the selection and reservation of routes in the early stages of station design so that interference with other plant is minimised.

The cables should be grouped and sectionalised according to their importance and sub-division is usually inevitable if complete shut down is to be guarded against. The disposition of the plant usually plays a large part in the choice of method of cabling to be adopted, but there are a number of features which should always be borne in mind no matter what method be considered. These are :—

(1) Cost and time of construction.
(2) Convenience and accessibility for extensions.
(3) Freedom from trouble and isolation of faults.
(4) Space required and ease of maintenance.
(5) Neat and pleasing appearance.

Methods of Cabling

(1) Laying in the ground.
 (*a*) Solid in compound filled troughs.
 (*b*) Direct.
 (*c*) Drawn into pipes or ducts.
(2) Racking on walls or overhead structures.
(3) Racking in tunnels.

TABLE 59. *Cable Data*

M.C.R. MW	Voltage kV.	No. of Cables per Phase	Cross Section of Cable. Square inches	Current per Phase. Amps.	Remarks
10	6·6	3	0·50	1,100	P.I.L.C. singleway cleats in basement.
15	3·3	3	1·3	3,300	P.I.L.C.
20	6·6	5	0·50	2,200	P.I.L.C. singleway cleats in basement.
20	6·6	3	1·00	,,	,,
30	6·6	4	0·85	3,300	P.I.L.C. singleway cleats in basement.
30	6·6	3	1·25	3,300	P.I.L.C.
30	11·0	3	1·00	1,950	P.I.L.C. jute served. Trefoil in trenches.
30	11·0	6	0·50	1,950	P.I.L.C. taped trefoil.
30	33·0	1	1·00	650	P.I.L.C. taped, trefoil, part in basement, part laid direct in ground.
30	33·0	2	0·40	650	P.I.L.C. taped, trefoil, part in basement, part in tunnels.
30	,,	2	0·6	650	P.I.L.C. major portion of route in trefoil, stoneware ducts (18-in. centres).
50	11·0	4	1·00	3,280	P.I.L.C. jute served. Trefoil in trench.
50	33·0	3	0 60	1,090	P.I.L.C. jute served. Trefoil in trench.
50	66·0 from step-up transformer	1	0·35	550	P.I.L.C. part waterproofed, trefoil. Oil-filled. Part outside, part in tunnel.
75	33·0 from step-up transformer	3 3	1·0 1·0	1,650	P.I.L.C. trefoil. Part outside, part in tunnel. Total of six cables per phase--serving two sections of switchgear.

If the choice is not dictated by the site conditions detailed costs of the various methods should be prepared.

Combinations of the methods often solve many cabling problems and are to be found quite frequently in modern practice.

The advantages of the first method are, low first cost, less possibility of trouble from fires and protection against falling *débris* is afforded. Better cooling will result in (*b*), but it has disadvantages (also applying to (*a*) and (*c*)) in that a greater site area is required and the need to keep accurate records of cable positions. The ground in which the cables are laid direct should be free from contamination otherwise maintenance charges may be unduly high. Moreover, where the site is limited, adaptability either of the second and third methods in case of extensions is restricted.

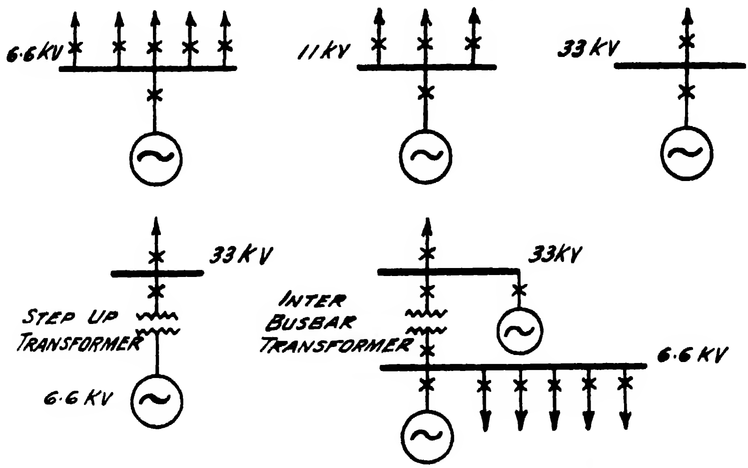


FIG. 480. Cabling Comparison for Various Voltages.

The use of fibre conduits for cabling both on and off the power station site is becoming increasingly popular and has the advantages of being lighter and easy to transport and handle, reduces installation costs since machined joints and longer lengths are adopted and lengths split longitudinally facilitate replacement or repairs. In some cases certain fibre conduits have disintegrated due to the material not being moisture proof and withdrawal of the cables has been difficult.

The duct system has the advantages of accessibility and neatness and it is advisable to provide spare ducts to allow for extensions. Draw-in pits of ample proportions should be provided to accommodate joint boxes and permit of two men working in them.

The overhead structure or wall mounting methods are relatively

low in first cost and maintenance charges. Further advantages are the ease and accessibility for extensions, the small site area required and no interference with other plant. On the other hand, the cables being racked on one structure or bridge are all liable to be involved in the event of fire. This risk may be reduced by using fire-resisting barriers. Further, exposure of cables to the direct rays of the sun affects their rating. A concentration of cables

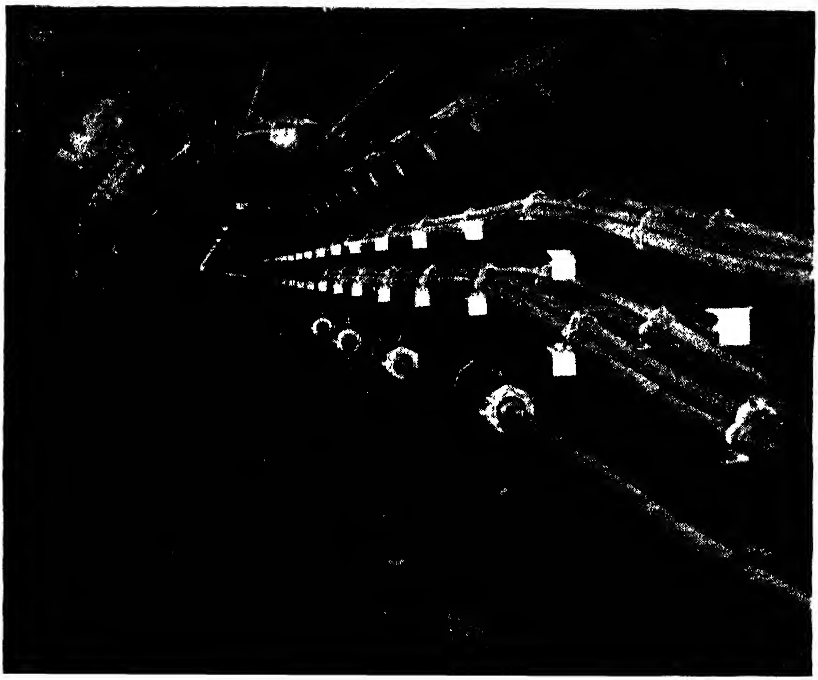


FIG. 481. Main Cable Tunnel, Battersea Power Station.

racked on one bridge or wall are also all liable to be involved in the event of enemy action from the air, and precautions have to be taken to deal with blast and splinters. The overhead and wall arrangements make quite a feature if properly laid out and designed and pipe-framework with twin-bar supporting straps is very adaptable. In addition to strength combined with lightness this method has the advantages that every cable can be handled individually both in erection and removal, is easily fixed and is suitable for multiple racking.

Adequately proportioned tunnels (Figs. 481 and 482) have been

included and have facilitated cabling. This system is convenient and accessible in case of extensions, since provision can be made in the early stages, and a small site area is required. Tunnels and trenches can be incorporated in the main building foundations and floors and arranged to serve the turbine, boiler and switch houses. The tunnels and trenches should be subdivided in such a manner that the fire hazard is reduced consistent with cost. Tunnels have been formed so that the cable ways are part of the tunnel construction. This method is more expensive than plain tunnels, but racks are not required and better fire protection is obtained. Modified forms of this subway or tunnel construction are also possible. The high first cost is generally in excess of other methods.

It may be necessary to drain and ventilate the tunnels and more expense is entailed by making special arrangements to avoid other sections of plant.

Alternator Main Cables. These cables have sealing ends or cable boxes with condenser bushings for higher-voltage alternators. The cables may be run horizontally from the block either at the end or sides, or alternatively drop vertically into a trench immediately below. To facilitate cabling, the terminal chamber may be arranged for side exit instead of the usual end exit. The turbo-alternator manufacturer who is usually responsible for the supporting arrangements, should be aware of this at an early stage in the work so that the necessary allowance can be made in the foundation block. Side exits may affect the design of the block and for civil engineering reasons some engineers prefer the end exit.

With lower-voltage machines it is sometimes difficult to accommodate the large number of sealing ends and in some cases special cable boxes have been designed to suit the limited space available in the foundation block.

The cables may either be grouped in trefoil formation or led out individually. All alternator circuits should be physically separated throughout their respective routes. Single-core, paper-insulated, lead-covered cables are the general practice. From data given it will be seen that even with higher-voltage machines three-core cables are out of the question and difficulties would be experienced with the connections at the alternator end. Three-core cables in parallel would be possible for smaller sets such as are met with in colliery or private industrial plants particularly if voltages of about 11 kV. are adopted. The route lengths of the cables to the alternator switchgear are usually comparatively short; further, three single-

core cables have a greater current carrying capacity than a three-core cable of the same conductor size since the surface area in contact with the air is much larger. The neutral cable is taken to its circuit-breaker, then to the resistor, or alternatively, direct to the main earth bar. The cables should be made-off with the sealing ends or cable boxes in position thus preventing any possibility of

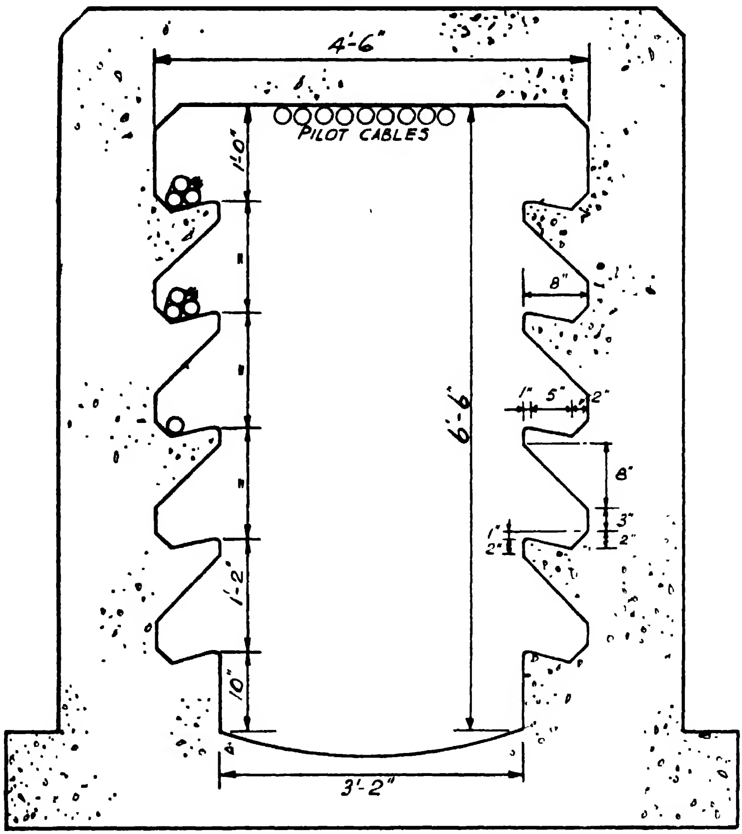


FIG. 482. Cable Subway.

straining the internal connections which might otherwise take place. The sealing ends should be suitable for the working voltage and be arranged to give the necessary electrical clearances to earth and between phases. Sealing ends designed for vertical mounting may not be suitable for horizontal use as internal corrugations in the insulator form undesirable voids and air pockets.

It is usual to work these large single-core cables with open-

circuited sheaths and for this reason the sealing ends are insulated from the supporting framework by a teak block or using an insulated gland. A danger of large current single-core cables is the heating effect due to circulating currents in the lead sheaths and magnetic flux induced in the gland plate of the cable boxes if it is of magnetic material. Non-magnetic glands and boxes are adopted for heavy current cables. With three-core cables such working conditions are avoided as the instantaneous sum of all the currents in the three phases is zero under normal conditions. The main direct current cables from the exciter to rotor slip rings, one going *viâ* the field suppression panel, are arranged to keep within the alternator foundation.

Feeder Cables. The feeder cables are of importance and their routes will depend upon the area to be served and the site conditions. The layout of the feeder switchgear will have a direct bearing on the method to be adopted for leading out the cables and the degree of separation justified. By using three-core cables more feeders per unit ground area will be possible since the spacing can be appreciably reduced.

Step-up Transformer Cables. These should be physically separated throughout their route to the switchgear and generally comply with the principles laid down under alternator cables.

Auxiliary Power Cables. The following groups are usual :—

(1) High-voltage cables serving station, unit and unit auxiliary switchboards.

These comprise cables from the secondaries of station and unit transformers to their switchboards, also cables to the primaries of unit auxiliary transformers and reactors. The station switchboard may be at generation voltage in which case all cables taken to the auxiliary transformers will be at this voltage.

All cables under this group are of primary importance, and care should be taken to sub-divide and maintain physical separation throughout their routes.

(2) High-voltage cables serving individual auxiliaries.

A number of auxiliaries will be supplied at high voltage, *e.g.*, large pumps and fans. Another special equipment is the electrostatic precipitator, this being operated at high-voltage direct current.

(3) Medium-voltage cables serving auxiliary switchboards.

Cables from the secondaries of all station and unit auxiliary

transformers come under this group. They are of the same importance as the high-voltage cables to their respective primaries.

(4) Medium-voltage cables serving auxiliaries.

All individual auxiliary power cables come under this group. Although they are not so important as the main cables feeding each switchboard, it is advisable to pay regard to the individual routes so that a reliable distribution system may be obtained.

Multicore Cables. Cables of the multicore type are used for control, protective and instrument equipments, the number of cores varying from two to fifty. Owing to the high induced voltages which may result from the opening of the solenoid circuits care should be taken in the design of these more important control circuits. Although the current may be comparatively high it is only required for a short period so that the cable current rating can be increased accordingly.

The remarks regarding sub-division and grouping apply equally well here.

Installation of Cables. One of the principal features of cable installation is the need for simple and easily-erected cable racking capable of adjustment to suit the varying site conditions, particularly if extensions are being made to existing plant. It should be possible to use any type of rack or cable, *e.g.*, porcelain, wood or brass cleats for plain lead-covered cables and supports for wire-armoured cables. Cabling is facilitated if the clamps or cleats can be turned to any angle to suit the routes of the cables, especially where it is desirable to transpose the phases in cables running in the vicinity of large masses of steelwork. It is helpful if additional ways can be superimposed on existing racks by double-tiering with only the use of longer studs and extra clamps or cleats.

The racking of cables on floors, walls and ceilings is simple, and, providing care is taken in the arrangement and spacing of the stirrups, a satisfactory layout will be obtained. If the spacing of the stirrups upon which the racks are fixed is too great the cables will tend to sag, resulting in an unsightly appearance. Racks spaced at intervals of not more than 3 ft. for cables of 1 in. external diameter and over and not more than 2 ft. for cables less than 1 in. external diameter is suitable. The supporting of cables in vertical positions calls for special attention both as regards type of cable and racking details. If the usual P.I.L.C. cable be used in a vertical position or on a slope the impregnating oil will eventually drain to

the lowest point on the route and probably produce sufficient internal pressure to burst the lead sheath or cable box. On very long vertical lengths it is preferable to use non-bleeding or drained cables. The spacing of the cleats will depend on the size, type and weight of cable, but a useful rule is to allow 500 to 550 lb. per cleat.

Assuming L = length of cleat, inches.
W = weight per cleat to be supported, lb.
D = overall diameter of cable, inches.

$$\text{then } L = \frac{W}{10 \, . \, D}.$$

Cleats should be of adequate size and not be too long or too narrow whilst wood cleats should have the tops well tapered, particularly if the cables are installed in shafts where water is likely to run down the cables. Where single-core cables are in trefoil formation it is advisable to provide intermediate clamps to prevent spreading of the cables if the short-circuit forces are of considerable magnitude.

Racks used for A.C. cables should be of brass or other non-magnetic material arranged to take three single-core cables of opposite phases, thereby reducing the induced sheath currents to a minimum.

The further the cables are apart the greater will be the heat generated in the lead sheaths due to eddy currents, and for this reason it is desirable to have the cables as close together as possible. If the cables are touching the current-carrying capacity will be reduced, due to the sheaths being shorted. Lead or bronze sheath single-core cables carrying A.C. may have their sheaths earthed at one point only, preferably at the middle, the sheaths being insulated from the supports at all other points. This prevents circulation of induced sheath currents. A further method of equalising induction is to turn the cables through 90° at the middle of the route. Where the cables of opposite phases are laid or grouped in trefoil formation no question of equalisation arises in view of the cables being symmetrically situated with respect to each other. Some cable manufacturers prefer the cable to be bonded at both ends as a precaution against accidental shorting of the sheaths at the ends. On very long lengths three-phase triangular or trefoil formation is preferable, the sheaths being bonded at intervals. By this means induced voltages in the sheath are reduced but sheath currents are set up which increase the heating. Although the induced voltage in the sheath is small the current may be such as to cause pitting

in the event of an accidental short at the ends of the sheaths. Bonding at both ends appears to be better than bonding at the centre or at one end. By bonding the sheaths of the cables together at one point, this induced voltage is anchored to a definite potential above earth and is a maximum at the point remote from the bond. It is better to avoid such standing voltages in the sheaths, for under fault conditions they may reach such a magnitude as to constitute a danger to life. Further, they may give rise to open sparking and cause pitting. The degree of insulation required is only small, two compounded paper tapes with serving placed over the lead sheath are sufficient to insulate the cables from the supporting racks and clamps. Special tape is wrapped around adhesively to the racks to prevent cables being damaged by stray currents. For lengths of cables laid direct in the ground, these can be given a waterproof covering of double compounded hessian-tape and together with the two paper tapes laid direct on the lead, would give adequate insulation between the lead sheath and earth. The lead sheaths of the three cables of each trefoil circuit may be bonded and earthed where the three cables fan out at each end of a run, but are insulated from earth at the glands of the sealing ends or boxes. Taking two examples in which 33 kV. cables were used for 30 MW alternators :—

(1) Route length approximately 72 yards (one—1 sq. in. per phase).
Insulated glands at both ends.
Bonded at both ends where cables splay out.
Earthed at both bonding points.

(2) Route length approximately 250 yards (two—0·6 sq. in. per phase).
Insulated glands at both ends.
Bonded at both ends of each group.
Earthed at one end only.

A recent installation comprising 52·5 MW, 11·8 kV sets is of interest. The alternator tails consist of 4 in. × ¼ in. solid copper strips per phase and the cables are in four groups of 3-core 1·0 sq. in. P.I.L.C. per machine. In tunnels the trefoil groups are kept together by special clamps of non-magnetic alloy, the cables being run with the lead sheaths in contact and insulated from the trefoil clamps by a wrapping of elephantide. The cables are earthed at the break of trefoil at each end of route and again at approximately the centre point, a band of lead being wiped to the lead sheaths and connected by copper strip to the station earthing system. From the 60 MVA machine step-up transformer (11·8/132 kV delta-star) 132 kV 0·3 sq. in. copper single core cables with 12 mm. oil duct and single rein-

forced lead sheath are used. For the tunnel runs the cables are single steel armoured with outer servings of fireproof compound impregnated tapes. They are run in close trefoil formation and are held by mine type cleats. The use of armouring on the single-core cables is especially notable.

The arrangement of the main single core cables at the ends of the route where they split up or fan out to connect transformers or alternators should receive careful attention. Where a number of cables per phase are used care should be taken to maintain as far as possible a proper geometric formation and to avoid the presence of steelwork in the direct field between phases thereby preventing eddy and hysteresis losses in the steelwork. Cases are on record where heating has taken place and non-magnetic sections have had to be included to break the magnetic circuits.

To avoid large sheath circulating currents due to the increased spacing between cables at these end sections the sheaths are left unbonded, the last bond being where the cables fan out. This spreading out increases the cable reactance and where a number of large cables per phase are used it is possible for the current to be unevenly distributed amongst them since badly arranged cables may produce unequal mutual inductance effects. The degree of inequality in current distribution which may be obtained is shown in Fig. 483. This represents the terminations of a short system of 1·0 sq. in. 6·6 kV. cables, in which the run is about 100 ft. The cables are in five three-phase trefoil groups reasonably close together for over 60 ft. of the route, the two end sections being about 20 ft., each with a mean spacing of 20 in. Bonding and earthing is carried out at both ends of the trefoil section, the terminations being insulated. Owing to the comparatively long ends of single core cable at wider spacing the effective reactance of these is greater than the trefoil grouping, and the variation in mutual inductance between different cores is sufficient to account for inequalities of some 20 per cent. in the circuit impedance.

For a 30 MW, 33 kV set with two cables per phase the cables are laid up in trefoil formation in non-magnetic cleats supported on brackets supported to walls. The cables are bonded together and earthed at each end of the trefoil run and the supporting brackets are earthed every 30 ft. along the cable route. At the sealing ends insulated glands are used, which are short circuited by metal straps but can be removed if required to eliminate the sheath currents at the cable ends.

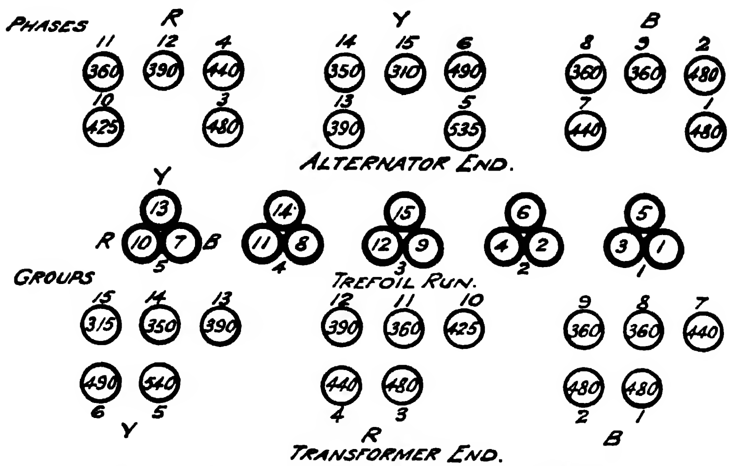


FIG. 483. Distribution of Current in Alternator Main Cables.

For single-core cables laid in trefoil the voltage to earth induced in the lead sheaths if these are earthed at one end only and insulated from each other throughout the route, is given by

$$E = I\,(0{\cdot}233 \log 10 \frac{S}{r}) \text{ volts/mile of single conductor.}$$

where I = current in amps.
S = axial spacing between conductors.
r = mean radius of lead sheath.

When the sheaths are bonded together at each end of the route there is no induced voltage to earth but circulating current flows in them.

TABLE 60. 5–1·0 *sq. in. Single Cables per Phase Bonded and Earthed at Trefoil Sections with Terminal Lengths Insulated*

Groups	Current in Amperes					Per Phase
	1	2	3	4	5	
Red . . .	480	440	390	360	425	2,095
Yellow . .	535	490	310	350	390	2,075
Blue . . .	480	480	360	360	440	2,120
Per Group . .	1,495	1,410	1,060	1,070	1,255	—

On oil-filled cables it is necessary to avoid earthing the lead sheaths through the conservator connections.

Where cables are laid direct in the ground they should have a 3-in. surround of fine riddled earth, sand or clay, and have the mechanical protection of a creosoted wood cover board or a cable-cover tile. Each cover should be closely butt-jointed to the adjacent covers throughout the lengths of the cable. If the soil is contaminated or chemically active special precautions should be taken to guard against corrosion of the lead sheaths. On very ashy or made-up sites all cables should be completely surrounded with 3 to 4 in. of puddle clay, unless special troughing arrangements are provided.

Cables laid in the ground on one large station site were treated as follows :—

All 66 kV. oil-filled cables (with corrosion-proofing protection)—laid solid in wood troughs (compound filled three S.C. cables per trough).

All 20, 11, 6 and 3 kV. cables (with corrosion-proofing protection) laid direct.

All 400-volt and multicore cables (2 hessian tapes and compound under armour and 2 hessian tapes and compound over armour) laid direct.

Special tubing is available which may be used for protection above or below ground and some of its features are : weather and corrosion resisting, waterproof, tough, flexible, light and vibration proof. The Pernax tubing is one type of such an insulation.

The distance between centres of 3-core power cables or groups of three single-core power cables should not normally be less than 18 in. This applies to cables laid direct in the ground, in pebble-filled trenches, and "solid" in bitumen. For cables in air there should be more than 6 in. between exteriors.

Cast iron, wrought iron, impregnated fibre, asbestos and stoneware ducts may be used for 3-core cables. Impregnated fibre, asbestos and stoneware ducts may be used for single-core cables. The bends of pipe or duct lines should be as easy as possible and where necessary split pipes should be used on bends, the pipes being fitted round the cable after installation.

If hard-wood cleats are used these should have all edges rounded off to prevent cutting into the lead.

The cleats should be treated with hot creosote or the like to guard against wood beetles, particularly if lead-covered cables are laid in direct contact with the wood. The beetles or larva, although

boring through lead covering do not feed on the lead but merely go through it as an obstruction in their paths. The grub is quite small and the hole it bores is only about 0·1 in. or so.

Elmwood has proved satisfactory since it is hard, of fine grain and not apt to crack. Teak is suitable but oak is not recommended, for it exudes acids which attack the lead.

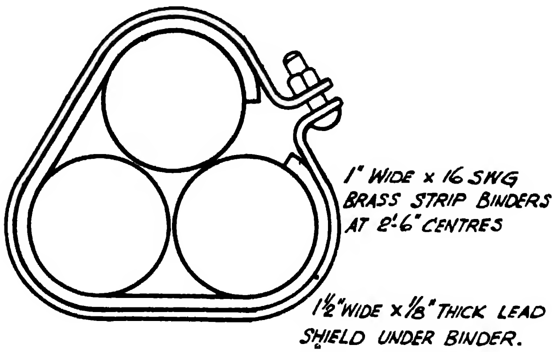


FIG. 484. Intermediate Cable Clamp.

Where cable runs are in close proximity to hot air or gas ducts, asbestos pipes prove helpful. Fibre, asbestos and stoneware pipes laid in the ground should have a 3-in. minimum surround of concrete. Where three pipes are laid to accommodate three single-core cables comprising one three-phase circuit they should be laid as close together as possible.

Auxiliary power and multicore cables which may have to pass

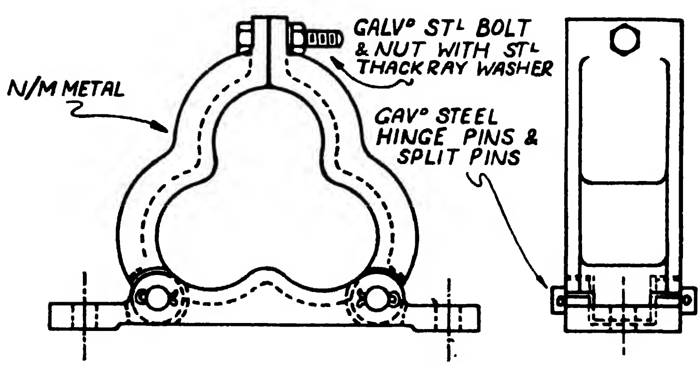


FIG. 485. Non-magnetic Clover-leaf Cleat for E.H.T. Cables.

under foundations can be catered for by the inclusion of clusters of pipes, with draw pits to allow the cables to be led out in any direction.

Where groups of auxiliary power and multicore cables are brought together they should be sectionalised in accordance with their importance.

Multicore control cables should be kept from the main power cables even though they may of necessity have to follow the same route. Trouble may be experienced where armoured control cables are laid in close proximity and touch unarmoured main cables due to transference of earth currents during fault conditions. Cable routes should be accessible throughout their length. Figs. 484–488 show typical details.

Fire Protection for Cables. Considerable thought has been given to the protection of the main and multicore control cables where they are likely to be subjected to burning oil. The most vulnerable points are the connecting lengths to switchgear and transformers.

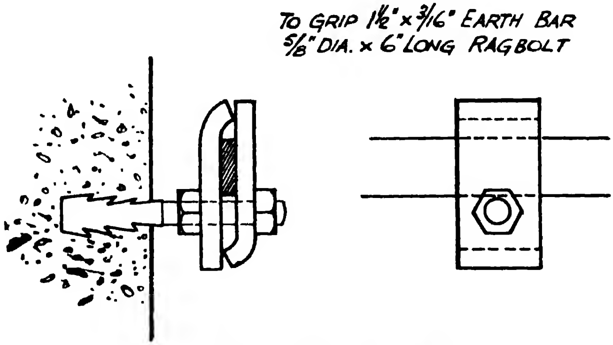


FIG. 486. Earth Bar Clamp.

Switch-house and transformer-annexe design influence the method of running the cables. Where cables are laid in trenches they may be protected from burning oil by filling the trenches with pebbles, granite chippings or sand.

From tests it appears that pebbles are more effective than granite chippings. Washed pebbles of ¾-in. size and upwards have been used for covering armoured cables and washed river sand for unarmoured cables. Pebbles have sharp edges and points which may damage the jute servings and lead. Where sand is used the cables may be adversely affected by restricted heating. Cases are on record where overheating of cables in sand-filled trenches has resulted in deterioration of cable insulation, the surrounding sand reaching a very high temperature.

Where sand is used a layer of pebbles should be placed in the bottom of each trench to facilitate drainage of oil. Where sand-filled trenches adjoin those containing pebbles expanded metal grilles may be placed at the joining points to hold the pebbles.

All exposed lengths of main cables in switch houses, basements and transformer bays likely to be subject to burning oil may be

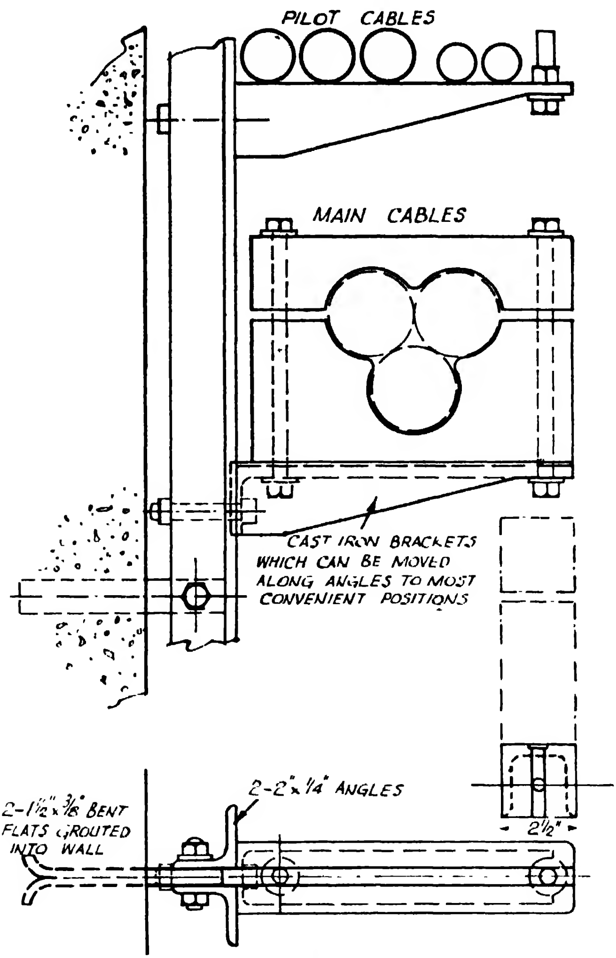


Fig. 487. Cable Racking Details.

treated with protective coverings of asbestos tape and given a coating of silica paint.

Before treating cables in this manner all outer serving should be removed and the armouring tape or wire perfectly cleaned.

Types of Cables. The classes of cables can be divided broadly into four sections :

(1) Extra high voltage.
(2) High voltage.
(3) Medium voltage.
(4) Low voltage.

Reference should be made to the Electricity Supply Regulations and also the Electricity Regulations under the Factories Acts 1937 and 1948 for definitions relating to voltages.

Extra high-voltage cables include all cables above 3,000 volts.

High-voltage cables include all cables above 650 volts and are usually of the paper-insulated type with plain lead covering, taped, together with additional steel wire or steel tape armouring for three-core cables.

Single-core cables will have plain lead covering with serving, although the latter is not always essential. Since its inception the impregnated paper cable has been mostly used for extra high-voltage work up to 33 kV. An important innovation was the screening of the individual cores of 3-core cables with perforated metallised paper which had the effect of eliminating so-called tangential stresses and converting the rotating electric stress field into a simple pulsating radial field. Where 66 kV. cables are used these are generally of the oil-filled type in which provision is made for the dielectric impregnating medium (low-viscosity compound) to pass in and out of the cable under a low pressure to compensate for expansion and contraction of the dielectric compound under varying loads and thereby prevent the existence of ionisation spaces. It is possible to increase the permissible working maximum stress from 40/50 kV. per cm. to 80/100 kV. per cm.

Gas-filled cables have been tried, the cable being placed in a lead sheath filled with dry nitrogen of between 10 to 15 p.s.i. Dry nitrogen with a negligible amount of oxygen is chosen as the most suitable gas to prevent oxidation or other chemical deterioration. Any damage to the cable sheath sufficient to cause a leak lowers the pressure and operates an alarm. If the leak is small, additional gas may be fed into the cable from standby high-pressure cylinders and repairs postponed. Such a cable is suitable for important feeders since it can be loaded to a maxiumum figure without deterioration.

Maintenance of pressure during transport, installation and service is of utmost importance. Problems of hydrostatic head pressures due to steep profiles are eliminated.

Components required for a gas-filled system are joints, terminals, pressure relays and pressure-regulating equipment. Stop or barrier

joints are not required as there is no head pressure with gas-filled cable although compound-filled terminals are used similar to solid cables except that a cork gasket semi-stop is included in the base. The semi-stop prevents leakage of the compound into the

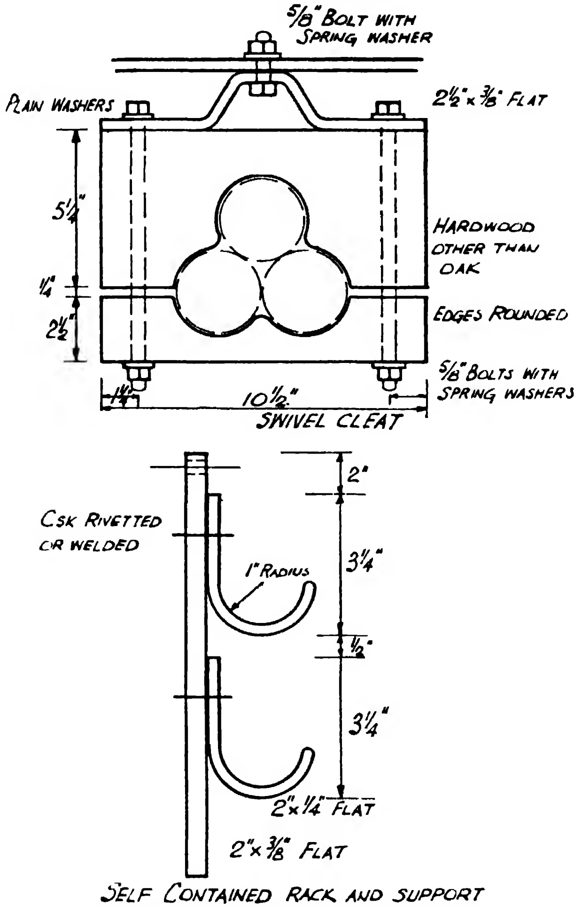


FIG. 488. Swivel Cleat and Self-contained Rack.

cable but there is sufficient seepage of gas pressure past this stop to maintain the whole terminal under pressure. A pressure relay is attached to one or both ends of the cable and gives an alarm should the pressure of gas in the cable drop below 10 lb. or rise above 15 lb. Gas volume in the cable is sufficient to take care of daily load-temperature cycles and re-adjustment for seasonal

ambient temperature is usually only necessary twice a year. Excessive gas pressure in the cable may be restricted by suitable venting arrangements.

The medium and low-voltage cables are paper-insulated, cambric-insulated or vulcanised rubber insulation, and in most cases lead-covered with or without protective armouring. The paper and cambric-insulated types are used for practically all auxiliary power and lighting work. Cambric is preferred for the boiler house where high temperatures obtain. The cost is slightly higher, but on short runs this is more than compensated for by the possibility of using cable clamps in place of more costly sealing ends. Trouble has been experienced with cambric insulated lead-covered cables when used for main exciter leads in alternator ventilating ducts, insulation failure and pitting of sheaths being noticeable. A non-bleeding paper-insulated cable may be used which obviates the use of cable sealing boxes. Drained cables have been used for 11 kV. although above this voltage it is permissible to have some variations of level without the necessity for a barrier joint. In any case a rise at one end is often balanced by a rise at the other end. Vulcanised india-rubber is adopted for almost all multicore control, protective and instrument cables. The cross-sections of the conductors being small, as many as fifty circuits can be grouped in one cable. All small wiring is V.R.I., whilst special heat-resisting V.R.I. cables can be used to advantage in the boiler house.

A special form of cable consists of an outer copper sheath filled with asbestos, the conductors being similar to an ordinary cable. This type is able to withstand dampness and intense heat and is specially suitable for boiler-house service.

Finish of Cables. There are many classes of cable on the market and a number are given to indicate the various types of finish :—

Class 1. Plain lead-covered.

Class 2. Lead-covered, served with one layer of paper and armoured with a layer of galvanised steel wires.

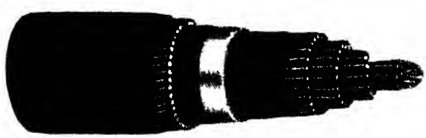
Class 3. Lead-covered, served with two layers of hessian tape and compounded. (Two fire-resisting tapes are sometimes used.)

Class 4. Lead-covered, compounded, lapped with two hessian tapes with layer of compound between and compounded over, armoured with a layer of galvanised steel wires, compounded, lapped with two hessian tapes with layer of compound overall.

Class 5. Lead-covered two paper tapes, one cotton tape, one hessian tape all pre-impregnated and each layer served in a suitable compound applied above the lead sheath in the order named. Serving for armoured cables—two hessian tapes compounded overall.

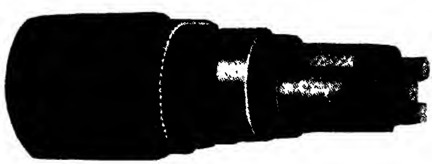
Class 6 (corrosion-proof cables). The lead sheath is compounded in the usual way with an elastic mineral pitch and served with a pre-compounded closely woven cotton tape. On this tape are wound several hard rubber cords (0·1 in. diameter) spaced from ¼ to ⅜ in. apart. The spaces between these cords are then filled with elastic mineral pitch and the cable is served, while the pitch is still plastic, with another closely woven pre-impregnated cotton tape which keeps the pitch in position. The lead sheath is thus completely surrounded with a layer of waterproofing material 0·1 in. thick and the hard rubber cords prevent decentralisation of the cable in it, thus protection can be applied to a lead-covered cable as serving only, or it can be applied under the armour, over the armour or both under and over. This is known as the Packer protection. The bedding on the sheath prevents damage by the armouring.

All waterproofing should be removed from cables situated inside buildings. Fig. 489 shows three types of cable.



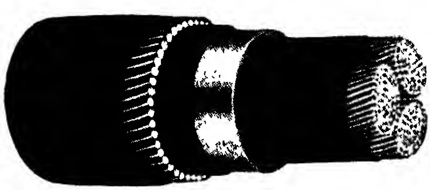
(1)

60-core Pilot-Auxiliary Cable, 660 volt. (may be impregnated paper or V.R.I.).



(3)

22 kV. P.I.L.C. cable designed on the "Hochstadter" principle in which the electric stress is radial in each core. This is achieved by surrounding each insulated core with a separate continuous, earthed, metallic screen.



(2)

Typical 3-core cable with wire armour and serving.

FIG. 489. Types of Cables. (Derby Cables Ltd.)

Current Rating. The current carrying capacity of a cable (apart from conductor section) will depend chiefly on the method of laying. Where three single-core cables are laid direct in the ground they

should be laid together in trefoil formation and bound together at intervals of say 6 ft. throughout their length. The trefoil formation should be such that two cables are at the top, since these have then only the heat of the one underneath, rising up to them.

Should the cables be racked on stirrups fixed along a concrete floor probably better cooling would result by arranging the trefoil formation with two cables on bottom. In some cases the relative position of the three cables are changed at each joint, complete transposition being effected in every three consecutive cable lengths. Where cables are run in air the heat is dissipated partly by radiation and partly by convection. The portion radiated tends to increase the temperature of neighbouring cables whereas that convected will only do so if the hot air rising from one impinges upon the other. For this reason it is not advisable to run one cable in the same vertical plane with another.

Some of the factors which influence the current-carrying capacity of a cable are : thermal resistance of ground, ambient temperature of ground (or air), depth of cable from the ground surface, proximity of other cables and their current loading, proximity of steam or other pipes, and a further factor which may have to be considered is the permissible voltage drop.

The data given in Tables 61 and 62 will serve as a guide, but it is advisable to consult the cable manufacturers and thereby determine the most economical size of cable to suit the conditions.

TABLE 61. *Cable Ratings for Different Methods of Laying*

Voltage kV.	Three-phase Load MVA	Current amps.	P.I.L.C.S.C. Taped Cables. Method of Laying. No. of Cables and Size per Phase. Square Inches.				
			Direct in Ground	Pebble-filled Trench	Solid in Bitumen	In Air Cable Tunnel	In Ducts
11	40	2,100	3–1·5 4–0·75 5–0·5	3–1·5 4–0·75 5–0·5	4–1·0 5–0·6	2–1·5 3–0·6 4–0·4	9–1·0 10–0·85 11–0·6
33	40	700	2–0·4	2–0·3	2-0·4	1–0·75 2–0·25	2–0·75 3–0·4
11	62·5	3,280	5–1·5 6–1·0 7–0·75 8–0·5	5–1·5 6–0·85 7–0·6 8–0·5	6–1·25 7–0·85 8–0·6	3–1·5 4–0·85 5–0·6 6–0·4	14–1·25 15–1·0 16–0·75
33	62·5	1,093	2–0·85 3–0·4	2–0·75 3–0·4	3–0·5 4–0·3	2–0·5	4–0·75 5–0·5

TABLE 62. *Approximate Current-carrying Capacities of* 66 *kV. Oil-filled Cables for Different Methods of Laying*

66 kV. Single-core Oil-filled Cables

Cross Section Area square inches	Current per Conductor when Laid Direct in Ground. Amps.		Current per Conductor. Amps.		External Dia. in. U.W.	
	1–3-phase Circuit per Trench	4–3-phase Circuits per Trench	Pipes	Racked in Air		
0·1	260	190	220	300	2·20	
0·2	370	280	320	450	2·30	
0·3	460	340	390	545	2·40	
0·5	580	440	500	690	2·70	
66 kV. Three-core Oil-filled Cables						
					U.W.	A W.
0·1	230	170	200	270	3·40	3·60
0·2	330	250	290	400	3·70	4·00
0·25	385	290	330	460	3·80	4·10

The auxiliary power cables vary over a wide range so far as sectional area is concerned. Sizes of from 0·007/3-core to 0·25/3-core are common, and single-core cables up to 1 sq. in. may be used. It is desirable to standardise cables although their application to a particular service may be in excess of that required.

With smaller cables the larger sizes have the advantage of increased mechanical strength, which is an asset. In selecting the size of cable due regard should also be paid to the characteristics under short-circuit conditions.

This will often determine the minimum section of conductor rather than the normal current rating. Apart from the normal current-carrying capacity the size to be used depends upon the value of the short-circuit current to be carried and also on the time that this current may flow.

At present there is no fixed figure of maximum current density, but manufacturers usually consider it advisable to work paper-insulated cables at a density not exceeding 80,000 amps. per sq. in. for one half second, or 55,000 amps. per sq. in. for one second.

Under short-circuit conditions damage to insulation by over-heating or by mechanical forces should be eliminated. The current densities suggested assume that the full value of short-circuit current flows for the time specified, whereas in practice this current will fall to a much lower figure at the end of half a second than that corresponding to the symmetrical current in the first few cycles.

In view of this it is often considered justifiable to work at a higher current density and figures of 120,000 to 150,000 amps. per sq. in. have been used. The time period will depend upon the protective gear setting which varies according to the plant and equipment protected.

The current ratings of cables together with particulars of grouping and routes are set out in the I.E.E. Regulations and Cable Makers' Association publications, to which reference should be made.

The multicore control and instrument cables also vary as regards core sizes and number of cores. Table 63 gives data relating to a 30-MW turbo-alternator main cables.

TABLE 63. *Cable Data*

30 *MW*. 33 *kV*. *Three-phase Turbo-Alternator*

Description	Phase	Neutral
Voltage between phases . . . . . . kV	33	—
Type of cable	Screened	Screened
Sectional area of conductor . . . sq. in.	1·0	0·1
Shape of conductor	Circular	Circular
Diameter of each wire . . . . . . in.	0·103	0·083
Diameter of core or approximate equivalent diameter in.	1 339	0·415
Radial thickness of dielectric on cores . . in.	0·35	0·35
Thickness of dielectric between core and screen . in.	0·35	0·35
Thickness of dielectric between core and lead sheath in.	0·35	0·35
Type of screen under lead sheath	Metallised paper and C.W.F. tape	Metallised paper
Thickness of lead sheath (minimum) . . in.	0·12	0·10
Diameter over lead sheath . . . . . in.	2·38	1·39
Diameter of completed cable . . . . in.	2·62	1·63

TABLE 63. *Cable Data—continued*

30 *MW.* 33 *kV.* *Three-phase Turbo-Alternator*

Description	Phase	Neutral
Weight per yard . . . . lb.	31	10
Normal drum length . . . . . yards	175	220
Minimum diameter of barrel of normal drum . in.	62	62
Minimum radius of bend round which cable can be laid . . . . ft.	7	4
Maximum continuous current carrying capacity per conductor laid direct in ground . . amps.	*682	206
Ditto—drawn into pipes . . . . . amps.	463	163
Ditto—when laid in racks in air at an ambient temperature of 25° C. . . . . . amps.	*830	209
Assumed maximum conductor temperature—laid direct in ground . . . . °C.	60	60
Ditto—drawn into pipes . . . . . °C.	50	50
Ditto—laid in racks in air . . . . . °C.	60	60
Electrical constants per core per 1,000 yards		
Resistance at 60° F. . . . . . ohms	0·0236	0·2427
Reactance at 50 cycles . . . . . ,,	0·07	0·13
Impedance at 50 cycles . . . . . . ,,	0·075	0·28
Maximum star capacity . . . . . mfds.	0 45	0 19
Maximum charging current . . . . amps.	2 7	1·13
Charging kV.A. at 33 kV. . . . . kV.A.	154	64·5
Insulation resistance per mile at 60° F. . megs.	190	440
Dielectric stress at surface of conductor kV. per cm. .	25·8	35·7
High voltage pressure test at works . . A.C. volts	50,000	50,000
Ditto—after laying and jointing on site . D.C. volts	60,000	60,000

* These ratings assume that the cables are laid or cleated in trefoil formation and touching each other and in ground are approximately 3 ft. deep. Ground of thermal resistivity of 120. P.I.L.C. with two fire-resisting tapes, specially compounded where laid in ground.

Cable Records. To facilitate the ordering and recording of all cables it is necessary to provide cable schedules. In a very large

station where there are numerous sub-divisions of voltages it is quite possible that a separate schedule will be justifiable for each voltage.

Taking the case of a 300 MW station where the first installation comprised 3–50 MW sets the following schedules were used and found helpful :—

66 kV., 11 kV., 3 kV., 400 V. and 110 V.

Typical power and multicore schedules are given in Tables 64 and 65. These schedules are also useful during the construction period and if desired may be used as progress charts.

General Notes. Bending radii of cables.

66 kV. Cables	25 times overall diameter
33 ,, ,,	25 ,, ,, ,,
22 ,, ,,	20 ,, ,, ,,
11 and 6·6 ,, ,,	15 ,, ,, ,,

Where 33 and 66 kV. cables have to negotiate difficult bends the cables should have extra insulation.

All cables run in air should be shaded from the direct rays of the sun.

Auxiliary Cable Comparison

	Cost	Current
Paper insulated lead covered (P.I.L.C.)	1·0	100 amps.
Cambric ,, ,, ,, (C.I.L.C.)	1·6	100 ,,
Vulcanised rubber lead covered (V.R.I.L.C)	2·7	60 ,,

Electrostatic Precipitator Cables. Extra-high voltage single conductor (tinned steel wire) P.I.L C. specially taped 66 kV. cable, screened M.P. type.

Size of conductor	19/0·08
Diameter over lead	1·862 in.
Diameter overall	2·06 in.
Minimum bending radius	35 times diameter over lead
Adjacent to joints	20 ,, ,, ,,
Insulation resistance per mile at 60° F.	1,460 megohms.
Conductor resistance per mile at 60° F.	3·52 ohms.
Capacity per mile	0·23 mfd.
Type of racks	teak blocks at 2 ft. centres

TABLE 64. *Power Cable Schedule*

..............................Electricity Department ....Power Station

Item No	Section of Plant	Route From	Route To	Type of Cable	Section square inches	Voltage	Dia. Over Lead	Dia. Over Armour	No. of Cables per Phase	No. of Cables Required	Route Length (yds.) Estimated	Route Length (yds.) Actual	Cable Length (yds.) Estimated	Cable Length (yds.) Actual	Remarks	Item No.

Schedule of Power Cables
for..............................

....
City Electrical Engineer.

Made by ....
Date ....
Approved ....

Drg. No. ....
Sheet No. ....
Revision ....

TABLE 65 *Multicore Cable Schedule*

.... Electricity Department .... Power Station

Item No.	Section of Plant	Route		Type of Cable	Total No. of Cores	No. and Section of Cores						Voltage	Dia. Over Lead	Dia. Over Armour	Cable Length (yds.)		Remarks	Item No.
		From	To			3/.029	3/.036	7/.029	7/.044	7/.052					Estimated	Actual		

Schedule of Multicore Cables for..	.... City Electrical Engineer.	Made by............... Date .... Approved	Drg. No.................................... Sheet No. .... Revision ....

Cable Boxes and Joints. Reference has already been made to cable boxes under "Transformers," Chapter XIII. To prevent the ingress of moisture to the terminal chamber and thus to the cable, a sealing or dividing box is provided. These boxes may be made of brass or other non-magnetic metal, cast iron or welded steel plate. The terminal chamber should be of ample proportions to permit of making off of good connections and holding the necessary insulating medium. An efficient seal must be included to prevent diminution of the insulating properties of the cable.

Some features to be observed in cable box design are :—

(1) Good joints and jointing materials.

(2) Adequate access for fitting stress cones on higher voltage cables.

(3) Cable sockets to have small countersunk hole ($\frac{1}{4}$ in.) in top to facilitate soldering.

(4) Expansion joints should be provided if there is any possibility of thrust from cables causing damage to bushings or insulators.

(5) Cable socket bolt holes should be elongated or so designed to eliminate erection stresses.

Cable boxes may be of steel plate, with glands, gland plate, and bushing flange of non-magnetic alloys. The design takes into consideration the iron losses in the box and the assembly is maintained within the prescribed limits of temperature rise. Such boxes have been found satisfactory for single-core cables carrying 600/800 amperes.

The soldering materials and flux should be chosen with care for in one case the core had a green corrosion product which was present in the outer layer and second layer only. A flux containing zinc chloride was thought to have been used when jointing.

Cable Box Compound. The compound or oil used for cable boxes and sealing ends should always be to the requirements of the cable manufacturer. Oil facilitates removal of boxes since they can be drained. Some particulars of compound used on a number of installations are given.

The compound for a 33 kV. cable box had the following characteristics :—

Flash point closed	220° C.
,, ,, open	225° C.
Viscosity, Redwood seconds	4,900 (140° F).
,, ,, ,,	450 (200° F.)
Coefficient of expansion per °C.	0·00065
Specific gravity at 20° C.	0·99

Specific inductive capacity	2·68
Breakdown r.m.s. kV	48 (20° C.)
2 mm. gap	40 (40° C.)
13 mm. spheres	40 (40° C.)
,, ,,	35 (60 °C.)
,, ,,	31 (80° C.)
Composition per cent. mineral oil. .	70
,, per cent. resin . . .	30

CHAPTER XVI

LUBRICATING, INSULATING AND FUEL OILS

THE most important oils required for power station services are the turbine lubricating oil and switchgear and transformer insulating oil. Turbine oil is referred to in Volume 1, Chapter IX, where the features of lubricating systems were outlined.

Turbine Oil. The importance of turbine oil is well known and any deterioration in its qualities very soon leads to disastrous results. Oil suppliers have been trying to produce the perfect turbine oil—one which will lubricate efficiently at all working temperatures without deterioration on any make or size of turbine and above all have a long life.

A good turbine oil is one which by its chemical constitution does not produce serious amounts of oxidation products or corrosive acids and has the ability to resist the effect of metallic accelerators.

High temperatures and the ingress of water should be eliminated if breakdown of the oil is to be avoided. Repeated heating gives rise to the formation of acid whilst the exposure of warm oil to air with water present causes emulsification. Leakages of water into the oil system may be due to steam from the glands, condensation of water vapour in the atmosphere or leakage at the oil coolers. The oil is heated by friction and also receives heat by conduction along the shafts. It is found that emulsified warm oil has a tendency to oxidise and this is assisted by the very fine film of oil at the bearings.

The oil system should be kept free from dust, dirt and other impurities as these have an oxidising action on the oil and more so when high temperatures obtain. Oil which has deteriorated rapidly forms sludge which impairs oil circulation in the system and its components. The oil used for lubrication is also used for the turbine governor and if sludging takes place the operation of this gear may be affected. The oil in a turbo-alternator has therefore to provide continuous lubrication of the shafts, thrust bearings and couplings when turning at high speeds (gears in very high-speed sets), also during barring or rolling periods, when considerable heat transfer takes place and in addition has to actuate the governor mechanism.

Some rather serious troubles have been experienced with lubricating system auxiliaries, probably caused by deterioration of the oil, and worm drives of the main oil pump damaged.

Two possible causes were put forward, one being high spot temperatures, and the other that electrolytic action had taken place. The insulation under the end pedestal of the alternator and the connecting oil pipes was improved and modifications made to the bearings to give increased oil flow. After this the bearing oil temperatures were greatly reduced and no further trouble was experienced. Apparently the increased oil flow was responsible for the improved results.

The problem of electrolysis has been the subject of much discussion from time to time and in some cases there has been evidence which led to the conclusion that electrolytic action was present. The passage of an electric current through oil causes the latter to become a very dark colour and, in some instances, very quickly. The oil so affected usually throws down a deposit which is of a fairly hard nature and dark chocolate in colour. The current in the case of an alternator is sometimes due to an unbalanced magnetic field which causes an induced current to be set up in the shaft. The method of preventing this has been given. Pitting of shafts is sometimes caused by shaft currents, such marks usually being black. A broken thermometer may result in mercury passing into the bearing and pitting from this cause is also possible and should not be confused with the electrolytic effects mentioned. Another trouble occasionally met is the formation of large amounts of froth which may be discharged from the vents in the oil tank. This is caused by aeration probably due to the rapid circulation of the oil through the system together with the presence of water and entrained air. The close co-operation of the oil suppliers and turbine manufacturers should be made possible so that the lubricating system and its components together with their design, layout and operation are fully explored in so far as they affect the life of the lubricating oil. Such factors as adequate venting, oil velocities, maximum temperatures, capacity of oil tank, capacity of purifier and many other items would be decided upon to the mutual advantage of clients, turbine manufacturer and oil supplier.

The deterioration of oil has received considerable attention and, speaking generally, is subject to chemical action by :—

(1) Oxidation by aeration and overheating.

(2) The entrance of steam or water to the oil system by gland leakages,

the formation of water-oil emulsions and the corrosion of the metals in the system.

(3) The interaction of oil oxidation products with the corrosion products to form metallic soaps.

There are numerous makes of oil and the advice of the turbine manufacturer should always be sought before making a decision. In some cases it is left to the turbine maker to supply the oil which has proved most satisfactory with the type of turbine to be installed. According to one authority a turbine oil should be a highly refined pure mineral oil which will separate

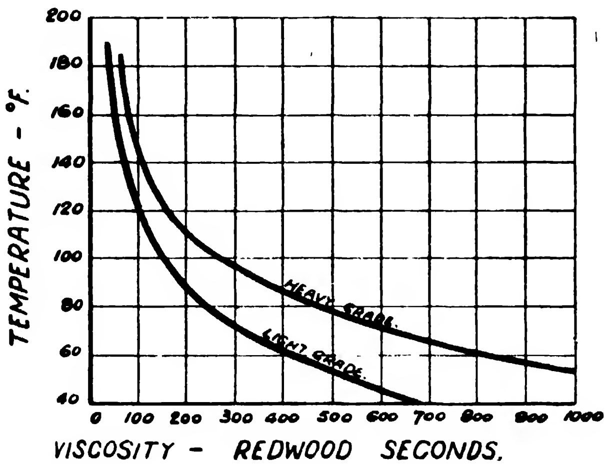


FIG. 490. Viscosity Curves for Turbine Oils.

readily from, and not form emulsions with, water. Oil refining has influenced the stability of oil and oxidation rate, for by drastic refining the resistance of the oil to oxidation is impaired and with it a reduced tolerance to metallic accelerators. The range of viscosity usually employed is shown in Fig. 490, the recent tendency being towards the lower scale of viscosities. It should also be free from easily oxidisable compounds, dirt and other impurities. The factors contributing to rapid oxidation are: aeration, water contamination, catalytic effects, overheating and electrolytic action.

The oxidation of turbine oil is generally autocatalytic and the products of oxidation themselves accelerate the process. The influence varies with each type of oil, *i.e.*, it varies with the chemical

balance between the paraffinic naphthenic and aromatic molecules which are constituents of all petroleum oils. The continuous use of lubricating oil without treatment of any kind will in a very short time reduce the lubricating properties to such an extent that it would be unsafe.

A typical set of test figures for one make of oil is given :—

Colour—Golden yellow : green bloom.	
Specific gravity	0·865
Viscosity at 70° F.	566″
(Redwood No. 1)	
,, at 140° F.	100″
,, at 200° F.	49–50″
Flash point (open)	450° F.
,, ,, (by Pensby Marten Closed Tester)	430° F.
Demulsification value (I.P.T.) . . .	45″

Three items demanding close attention are : life of the oil proposed, initial cost and amount of make-up oil required. The latter may be appreciable and in any case most turbine makers recommend that if good results are to be obtained and to prevent the accumulation of sludge or water in the oil tank and pipes, a small quantity of oil should be drawn off periodically from the oil tank and replaced by fresh oil. This should be done when the turbine has been standing for some hours.

Inhibitors for Turbine Oils. The addition of organic compounds has been made in an attempt to reduce the rate of oxidation. An inhibitor is anti-oxidant which materially lengthens the useful life. The properties which such compounds should possess are generally as follows :—

(1) They should be soluble in the oil at all working temperatures.
(2) Provide maximum effectiveness at low concentration.
(3) Be insoluble in water over all working temperatures.
(4) Not form reaction products which themselves are harmful in the system.
(5) Must not change the physical properties of the oil.

The amount of inhibitor added to the oil depends upon the organic compound used and varies from 0·05 to 0·10 per cent. The rate at which the inhibitor is used up varies with working conditions and the added organic compound, but in general the addition of new oil to make up oil losses in the system will provide the requisite

amount of inhibitor. To ensure good performance of the oil in service when changing from ordinary to inhibited oil it is essential to flush out the system.

Amongst the chemical compounds which are found to be applicable to turbine oils as inhibitors are polyhydroxy aromatic compounds, organic sulphur compounds, organic esters, phosphates, phosphites and organic metal salts.

Switchgear Oil. The oils for use in circuit breakers and transformers are mineral oils obtained from crude petroleum by fractional distillation. The insulating oil for circuit breakers calls for little comment since it is almost trouble-free. Care should be taken to prevent the ingress of moisture and regular testing will bring to notice any reduction of dielectric strength. The frequency with which the oil should be renewed in the tanks depends chiefly on the service which the circuit breakers is called upon to perform. A circuit breaker which has to deal with frequent short-circuits should be given special attention whereas one which is rarely opened on load and seldom called upon to break a short-circuit, the oil may well remain in the tank for two or more years before needing to be changed. Carbonisation deposits mixed with the oil form conducting paths, and if in sufficient quantity would cause a fault to earth, gases would probably be generated and result in an explosion in the tank. Overhaul of circuit-breakers which have operated in clearing faults, including changing of oil, is necessary. Successive operation of circuit-breakers under fault conditions without change of oil and other routine maintenance leads to tracking troubles and subsequent failure of breakers. Overheating on a circuit-breaker, particularly in the tank, is seldom experienced. Carbonisation may be noted by visual inspection and colour charts are sometimes used where all the oil inspected is of similar type, making possible the interpretation of the colour of consistent colour. If the oil is allowed to remain for long periods at a very low temperature emulsification is possible. The switch-houses should therefore be kept at a reasonable normal temperature, 45° F. being about the safe minimum, and 50° to 60° F. the normal average. The class of oil used will also have some bearing on this.

The class of oil varies and standard specifications are available which may be referred to. Oils for insulating purposes are divided into two classes " A " and " B." Class " A " oil is at times referred to as " non-sludging " oil and is suitable for use in transformers in which the working temperature of the oil, measured by thermo-

meter, exceeds 176° F. It is also suitable for use in oil circuit-breakers in which the working temperature exceeds 158° F. It may be used with advantage in oil circuit-breakers above 500 amps. capacity having their main contacts under oil and operated for long periods near their rated currents or in hot situations. Class " B " oil is suitable for use in transformers in which the temperature of the oil does not usually exceed 167° F. and for general use in oil circuit breakers not subjected to conditions requiring the use of class " A " oil.

Some authorities use class " A " oil and others prefer class " B_{30} " even for extra high-voltage switchgear.

Some of the information given under " Transformer Oil " is also applicable to switchgear.

Transformer Oil. This oil is much more liable to deterioration than switch oil since transformers are repeatedly loaded and unloaded throughout every hour of the day and, further, vibration may result in failure of core insulation. Prolonged overloading and high temperatures cause deterioration of the oil and one effect of this is the formation of acid. The failure of core bolt insulation may result in intermittent sparking with consequent deterioration of the oil. Explosive gases may be formed and care should always be exercised when opening up or working on transformers where trouble has been experienced or the oil is found to have deteriorated. Samples of oil should be drawn periodically from transformers for testing and be preferably taken from the bottom of the tank. Some insurance companies prefer to take one sample per year, whilst a number of manufacturers suggest that the tank cover be removed once during the same period to ascertain the general condition of the interior. In this way the upper structural parts of the core and the underside of the cover can be examined for traces of sludge or corrosion.

Breathers, if fitted, should also be examined to ascertain the condition of the chemical filling. In silca-gel breathers, indication is given by the changing of the coloured crystals from blue to pink. The gel may be reactivated by removal from the breather and heating to a temperature of 150° to 200° C. for two or three hours, or until the original blue colour reappears. Here again there seems to be some difference of opinion as to the class of oil to be used. Both class " A " and class " B " oils are used although some engineers are of the opinion that the former is prone to the formation of acids apparently due to its higher degree of refining. The fact that acid is present may

in no way affect the dielectric strength of the oil as will be observed from the following figures :—

Dielectric Strength	K.O.H. per gramme of oil
46 kV.	1·43 mg.
47 „	1·87 „
34 „	0·89 „
38 „	0·05 „
59 „	2·71 „
38 „	0·96 „
18 „	0·22 „

(K.O.H.—pure potassium hydroxide)

Authorities appear to differ on the figure at which it is safe to continue with oil of a known acid content. The acidity of an oil may be determined by a neutralisation test using potassium hydroxide, and when the neutralisation number as defined in standard specifications exceeds a predetermined value the oil should be purified by other methods in addition to centrifuging or filter press methods. If an oil has a neutralisation number of 0·8 it means that 0·8 mg. of potassium hydroxide is required to neutralise the acid in one gram of oil. One authority has suggested that oils having an acidity value of 1 to 1·5 mg. K.O.H. per gramme of oil should be discarded. American authorities suggest minimum requirements for oil beyond which reconditioning or replacement is desirable as follows :—

(1) Dielectric strength, 17 kV. (standard 0·1 in test).

(2) Acidity : (*a*) Transformers, 0·9 mg. K.O.H. per gramme of oil ; (*b*) oil circuit-breakers, 1·5 mg. K.O.H. per gramme of oil.

Various tests for acidity have been put forward and two are given for reference :—

(1) A test tube is partly filled with oil and heated gently on a Bunsen burner ; if the oil tends to turn black it would indicate the presence of acid.

(2) Taking a figure of 1 mg. K.O.H. per gramme of oil, pour 20 c.c. of oil into a 50 c.c. graduated stoppered measuring cylinder and add 30 c.c. of a spirit solution of caustic potash of known strength tinted pink by the addition of a few drops of phenolpthalein. Shake the mixture, and if the pink colour is just on the point of disappearing, the acidity is about 1 mg. K.O.H. per gramme of oil. If the pink colour is unchanged, then the acidity figure is below that named, or if the colour is discharged almost immediately, then the acidity figure is very much higher.

For further details reference should be made to B.S.S. No. 148/1951.

Insulating oil is a light coloured, sometimes colourless, mineral oil which should have the following properties :—

(1) Absence of moisture.
(2) Absence of tendency to sludge.
(3) High-flash point.
(4) High dielectric strength.
(5) High specific resistance.
(6) Neutral reaction.
(7) Absence of chemical impurities.
(8) Low viscosity.

The presence of moisture greatly reduces the dielectric strength of the oil and there is a further risk that the moisture may be deposited on the windings resulting in reduced insulation resistance. Tests show that a moisture content of less than 0·1 per cent. (a quantity which can be absorbed by oil) will reduce the dielectric strength to one-fifth of that for similar dry oil. Good resistance to emulsion is also important so that any materials, especially water entering the oil, will not be held in suspension, but will settle or separate from the oil. The cause of the formation of sludge in transformer oils is not yet fully understood but it appears probable that it results when oxidation of oil takes place at high temperatures. It is possible that a good grade of transformer oil will not produce sludge at temperatures below 160° F. Sludge in oil adversely affects transformers by :—

(1) Clogging the cooling ducts.
(2) Lowering the flash point.
(3) Increasing the viscosity of the oil, thereby reducing transference of heat from the windings.

Oils left in contact with the atmosphere often deposit sludge and the presence of copper acts as a catalytic agent, in promoting this formation.

To minimise the danger of fire risk the oil should have a high flash point and as a general rule the flash point should not be less than twice the maximum temperature reached by the transformer in normal working. A figure of 290° F. has been suggested as a minimum. The presence of impurities or moisture in the oil may considerably reduce the dielectric strength. The specific resistance is measured in megohms, and the presence of alkaline or acid

impurities will have the effect of considerably reducing the specific resistance. Freedom from acid or alkali and elements that are harmful to the insulation or conductors is desirable. Chemical impurities can be detected by chemical tests in the laboratory but generally the effects of impurities will be to reduce considerably the dielectric strength of the oil and possibly to affect the varnish on the windings. The oil should be capable of free circulation to effect a ready transference of heat from the windings to the tank of the transformer. The formation of sludge which remains suspended in the oil may bring about an increase in the viscosity and a reduction in the transference of heat from the windings with resultant higher temperatures.

Insulating Oil Tests. The standard tests should comply with B.S.S. No. 148. The following testing methods are given for reference :

WELLFIELD POWER STATION

CHEMICAL AND TESTING DEPT.

....195 .

LUBRICATING OIL TEST REPORT

Sample and Serial No. .				
Specific Gravity at 60° F.				
Viscosity : Red, secs. at 70° F. . 140° F. . 200° F. .				
Flash Point (closed test), ° F				
Acid value . . .				
Moisture . . .				
Demulsification No. .				
Appearance . . .				
Colour				
Remarks . . .				

Signed.................................

Wellfield Power Station
Lubrication Data
No. 4—30 MW Turbo-alternator

Week ending..............................

DAY	DISCHARGE OIL TEMPERATURE °F.						OIL TEMP. °F.		OIL PRESSURE Lb.			OIL COOLERS				OIL PURIFIER		OIL TANK	OIL MAKE-UP	LOAD MW.	REMARKS
	H P.		L.P		Altntr.		To Cooler	From Cooler	Main O.P.	Brg.	Pilot	Water in °F.	In use			Hrs. Run	Wt. Slge.	Water, Pints.	Galls.		
	1	2	3	4	5	6							1	2	3						
SUN.																					
MON.																					
TUES.																					
WED.																					
THURS.																					
FRI.																					
SAT.																					

Readings are those taken during maximum temperature of oil to coolers.

Signed......................................

Charge Engineer

Dielectric Strength Test.

Oil is tested for dielectric strength in a standard glass testing-vessel between two spheres of 13 mm. diameter, 4 mm. apart. The vessel which must be clean and dry is almost filled with the oil at a temperature of 15° C. to 20° C. and the voltage slowly raised to 30 kV., at which value it is maintained for one minute. If a break-down of the oil, which is indicated by an arc, does not occur at or below 30 kV. the oil is deemed to have passed the test satisfactorily. Preliminary sparking not developing into an arc may be ignored.

BELLE VUE POWER STATION

CHEMICAL AND TESTING DEPT.

......................................195 .

INSULATING OIL TEST REPORT

Sample and Serial No. .					
Specific Gravity at 60° F.					
Redwood Seconds at 60° F. . . .					
Flash Point ° F. . .					
Acidity . . .					
Moisture . . .					
Heat Loss, per cent. .					
Deposit . . .					
Colour . . .					
Remarks . . .					

Signed..................................

If no other apparatus is available, a dielectrometer may be used according to the instructions supplied with the instrument.

Approximate tests to determine the presence of moisture are as follows :—

(1) The sample of oil should be put into a clean dry glass vessel and allowed to stand for about forty-eight hours. If moisture is present in any

considerable quantity it can be readily detected by visual inspection as it will tend to separate into a layer at the bottom of the vessel. A sample should be clear and bright. Cloudiness indicates moisture.

(2) Gently heat a clean test-tube one-quarter full of oil over a burner. Any crackling will indicate the presence of free moisture. Alternatively, a sample of oil can be heated by introducing a metal rod at a temperature just below dull red. If the immersion is accompanied by a crackling, free moisture is present in the oil.

(3) Anhydrous copper sulphate added to a sample of oil takes a blue tint on contact with moisture.

(4) A small piece of sodium placed in oil will give off hydrogen bubbles in contact with moisture.

Sludge Test. This test is carried out to ascertain sludging capacity of the oil. A sample of air (which has been suitably treated with various agents) is drawn through a flask containing the oil to be tested and in which a cylinder of copper is inserted. It is maintained at a temperature of 150° C. for about forty-five hours and after further treatment with benzol the residue (which is sludge) is taken and expressed as a percentage over the specific gravity of the oil.

Drying and Cleaning of Insulating Oil. Transformer and switch-gear oil may eventually reach the stage where purification by the usual methods of centrifuging and filter press treatment are inadequate as these remove only the moisture, carbon and sludge. Oil exposed to air and heat also forms within it an organic acid which reduces the resistance to emulsification and allows moisture to remain in suspension. This acid condition gets progressively worse and cannot be removed by the centrifuge and filter press treatment, but requires an additional process of neutralisation or removal. Oil deterioration or the changing of some of the desirable properties may be due to the following causes: (1) Ingress of water; (2) Oxidation due to exposure to air and heat, causing sludge formation and the gradual formation of organic acids which decrease the resistance of emulsification; (3) Carbonisation due to arcing; (4) Improperly dried or incorrect type of insulating varnish. If the acid value of the oil is low it is possible to recondition it by drying and filtering and so bring about considerable saving in cost. Oil purification plant is necessary for dealing with both the transformer and switch-gear oil and it is usually placed in such a position as to meet the requirements of both. It comprises oil pumps, clean and dirty storage oil tanks, strainers and filters. Fig. 491 shows a diagram of connections for a large equipment.

The filtering equipment consists of a centrifugal filter with heater and pump, and an auxiliary filter press is included which may be used independently of the centrifugal filter. The filter with heater and pump form a complete and portable unit. The

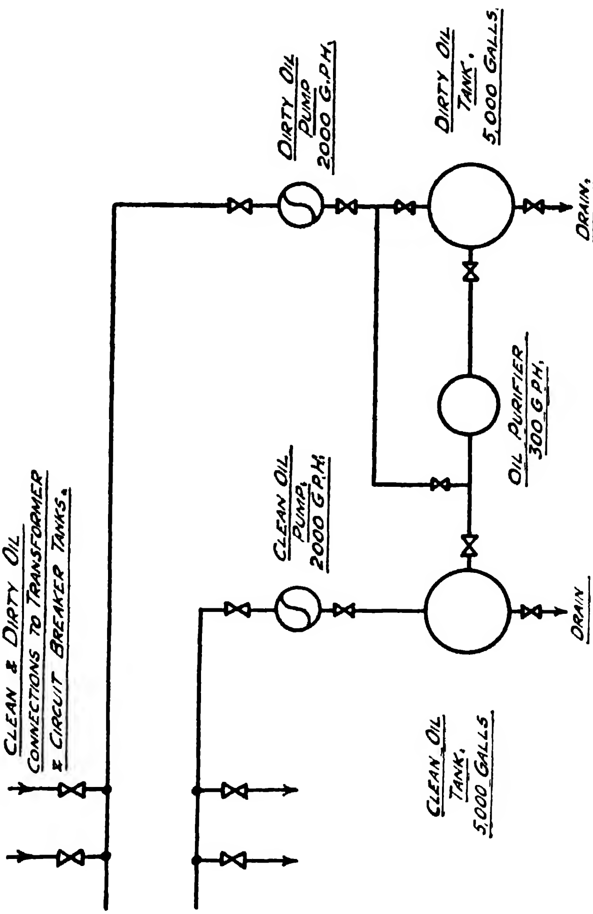


FIG. 491 Diagram of Oil Filtering and Storage Equipment.

pipe lines and tanks should be thoroughly cleaned and flushed with oil before filling up, and rubber hose is not recommended on account of its sulphur content. The storage tanks may be buried or housed in a separate building. These tanks should be air-tight but fitted with an oil-sealed overflow and a breather similar to that used on transformers. The system should be designed to eliminate

air locks and means should be provided for the removal of entrapped air. An oil level indicator, sampling cock and facilities for access and safe and easy cleaning are also necessary. The larger equipments are fixed in a permanent position, piping being connected to the switchgear and transformer annexes. Filter presses are of various types, one consists of a series of flat frames with filter papers between, the whole being tightly held together. The oil to be filtered is forced by the pump through the filter papers which intercept all sediment and sludge, and also absorb any moisture which may be present in the oil. After use the filter papers can be cleaned, dried, and afterwards packed and sealed to prevent absorption of moisture.

Before oil, which has been stored, is used for transformers or switchgear it should be tested for the presence of moisture, and in some cases it may be necessary to filter new oil prior to use. New oil should test at least 30 kV. (0·1 in. standard) and should not exceed 0·05 mg. K.O.H. If an oil press or oil separator is not available the oil may be dried by heating to 105° C. by means of immersion heaters. The temperature must be raised at a rate not exceeding 20° C. per hour to avoid carbonisation, and the final temperature should be maintained for five hours. The oil must be tested again for moisture after it has cooled. The sides of the tank may be covered to prevent loss of heat and the tank cover should be removed during heating to allow vapour to escape.

Methods of Reclaiming Oil. Methods of refining oil include processes using fuller's earth (a clay found in America) together with some chemical to counteract the acid and a method using activated alumina is also used. In one method using fuller's earth the oil and activated carbon are pumped into the mixing tank, heated and thoroughly agitated. The mixture is then centrifuged to remove free water and solids. The oil is reheated and mixed with a second reagent, sodium silicate, and again centrifuged. After again being reheated, the oil is mixed with fuller's earth, agitated, and then centrifuged for clarification.

The active alumina method is a physical process requiring slow, thorough penetration of the granules and is best suited to continuous maintenance of transformer oil. This may be done by placing sacks of activated alumina in the transformer tank or special tanks and circulating oil through it. Activated alumina (Al_2O_3) is a highly porous, hard, durable granular substance with absorptive properties, which are effective in removing acid from oil, but not sludge. The

saturated activated alumina may be recovered by heating in a ventilated retort or oven at a temperature of 350° to 600° F. Some useful information is given in the *Electrical World* (July 26th, 1941) relating to oil reclamation.

Transformer oil has been heated to 180° F. in a mixing tank (with a turbulator) containing 1 per cent. soda-ash and water after which it was centrifuged twice. Turbine oil after some sixteen years service was treated in a similar manner and rendered suitable for continued service.

Fuel Oil. There is usually very little trouble with this oil providing certain conditions are fulfilled. In some stations difficulties have been experienced due to gumming up in cold weather thus impairing the efficiency of combustion. The viscosity of the oil should be such that it is suitable for use in both summer and winter seasons. Such a fuel oil can be obtained and this obviates the necessity for the inclusion of hot water or steam heating.

Each pulverised fuel boiler has at least one lighting-up burner operating on the atomising system and usually capable of raising the temperature of the combustion chamber from cold to a temperature which will maintain the combustion of the lowest volatile fuel within fifteen to twenty minutes.

Adequate stocks of oil are essential, and if possible the storage tanks should be placed in a convenient position just outside the boiler house away from any other plant in which fire is likely to originate. The tanks should be of robust construction and be dust proof. In some stations the storage tanks have been placed on one of the higher platforms in the boiler-house so that use could be made of the available head and render a pump unnecessary. Provision has been made to guard against the possibility of stoppage or interruption of the coal supply. This has been done by means of change-over to oil fuel by the inclusion of oil-firing equipment. Taking the case of 8/125,000 lb. per hour boilers, three oil storage tanks, each of 3,500 tons capacity, are provided, and the oil firing equipment consists of four oil burners and air registers per boiler, each burner having a capacity of 2,330 lb. of oil per hour, or a total capacity for firing of over 33 tons of oil per hour for the eight boilers. The boilers are of the chain grate stoker type.

Further information relating to oil burning plants is given in Vol. 1, Chapter VII.

Typical lubricating and insulating oil data and report sheets are included for reference.

CHAPTER XVII

STATION AUXILIARIES

The station auxiliary plant load, or works load may represent anything from 4 to 8 per cent. of the station load. This may be broadly divided into the following sections :

Boiler auxiliaries	40 per cent.
Feed pumps	15 ,,
Circulating water auxiliaries	25 ,,
Coal and ash auxiliaries	5 ,,
Turbo-alternator auxiliaries	15 ,,

The auxiliary plant will vary in each station due to site conditions, particularly the circulating water and coal- and ash-handling auxiliaries ; while the steam conditions obtaining will affect the feed pump power. Considered on a comparative basis, increase in steam pressure will in general effect a saving in circulating water pump power since the steam to be handled by the condenser will be reduced due to higher turbine overall thermal efficiency and a greater number of bleeding points to feedheaters. The use of cooling towers or a river will materially affect the circulating water pumping and screening plant power. The circulating pump power is at least doubled but the air pump power (rotary ejectors) would be lower on account of the lower vacuum with cooling towers.

Reheat turbines require less auxiliary power largely because low steam consumption reduces the power requirements of the boiler feed pumps.

The factors governing the design of auxiliaries are the same as those controlling the choice of the main plant, that is, they should be reliable and economical. When a main unit (boiler or turbo-alternator) is running the whole of the associated auxiliary plant is working at a fairly high load whatever the load be on the main unit, therefore due regard should be given to economy in this direction.

Plant auxiliary power supply should be adequate when abnormal system or station conditions obtain such as frequency or voltage that is either low or high.

The saving effected in auxiliary power represents an increase in heat efficiency for the station. Although the coal- and ash-handling

plant auxiliaries are by far the smallest, they can, if properly designed, be responsible for effecting considerable savings in the cost of the fuel and refuse handled. These financial savings can in turn be reckoned on the basis of saving in heat efficiency and are worthy of consideration.

On reviewing the list of consumers of an undertaking it will be observed that the total auxiliary power units or works units very nearly approach those of some of the largest single consumers.

Considerations of Design. The problem of designing a reliable and economical auxiliary scheme is capable of many solutions. If a new station is contemplated the initial conditions are probably of much more importance than if it is an extension since these will determine to a great extent the direction in which all future extensions to the auxiliary system shall proceed. Full consideration must be given to the ultimate station capacity if standardisation and simplicity are to be maintained throughout. Sight must not be lost of the operating staff for of all power-station plant the auxiliaries usually call for much of their time and attention in so far as detail work is concerned. The simpler the system the better it is for the operating staff, providing safety is not impaired. The electrical layout seems to receive much attention, particularly in regard to methods of supply to the various sections of plant, and the requirements demanded under abnormal conditions. The steam auxiliaries are equally important and should go hand in hand with electrical services. Each station will have to be considered on its own and full account taken of local conditions. The fact of installing first-class switchgear, transformers, cables, motors, pumps, fans, turbines, etc., will in no way ensure that an ideal auxiliary scheme will result although the first link in the chain will have been well made. The final scheme, which is usually a combination of a number of systems, should be simple in every respect if reliability and efficiency are to be achieved. Automatic and remote control systems have proved successful in many stations effecting improvement of plant efficiency and also lightening the physical tasks of the operating staff. It is sometimes thought that the chief idea behind the installation of automatic gear is the saving of labour which normally is effected. The object of automatic gear is to increase the reliability and efficiency of service apart from any saving in labour costs. It is true that it may result in further unreliability if the automatic apparatus is unsuitable and is aggravated if it is not properly maintained. Before deciding on large schemes involving an immense amount of

intricate and complicated equipment consideration must be given to the staff it will necessitate and the savings accruing.

Automatic starting of idle stand-by services is desirable wherever it can be adopted in a simple and reliable form, an example being the use of electric and steam-feed pumps. Motor operation of large valves conserve man power during shut-downs or other abnormal periods.

The importance of the auxiliary plant and the methods of drive adopted justify special consideration, and some of the factors to be borne in mind are :—

(1) Reliability.
(2) Simplicity and safety.
(3) Attention and maintenance required.
(4) First cost.
(5) Effect on station overall efficiency.
(6) Operating costs, including charges on capital.
(7) Effect on feed system characteristics and heat balance.

Methods of Driving Auxiliaries. The auxiliary plant may be grouped as follows :—

(*a*) Steam-driven auxiliaries.
(*b*) Electrically-driven auxiliaries.

Fig. 492 indicates the principles whilst Fig. 493 shows the chief auxiliaries.

In comparing the relative merits of these it will be found that it is impossible to lay down any hard and fast rules which will apply to all cases or to all classes of auxiliary plant, this being partly due to the widely different conditions under which the plant has to operate and partly on account of the effect which the general design of the station has on this question. The trend in recent years has been from steam to electric drive, and no doubt this has been due to the increased confidence in the reliability of the latter and also to the simplicity and flexibility of this drive, together with the important changes in boiler and turbine practice. Objections to steam drive for normal, as distinct from stand-by use, include the relative inefficiency of small turbines and the difficulties associated with high steam pressures and temperatures. Small steam pipes, traps, drains and valves have to withstand high steam pressure and temperature and are subject to leakage, giving rise to increased attention and high maintenance charges. An electric cable is a much cheaper and simpler method of conveying power than a steam

pipe, although the cost of switchgear and possibly a transformer has to be allowed for.

If electrically-driven auxiliaries be adopted it will be necessary to increase the capacity of the main units by about 5 to 10 per cent. or, alternatively, this amount of special generating should be installed. Whichever method be employed the cost of the additional auxiliary generating plant must be debited against electrical auxiliaries, as steam-driven plant merely requires the provision of

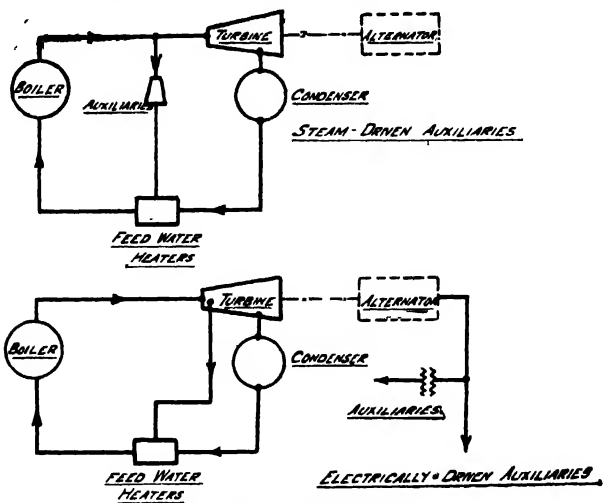


FIG. 492 Auxiliary Drives.

extra boiler capacity. Some of the factors influencing the choice of electrical drive are :—

(1) Easier control of the heat cycle.

(2) Facilitates more efficient station design by permitting all the steam required for feed-water heating to be taken from the main turbine by stage bleeding. Make-up water is reduced.

(3) Favoured for the essential auxiliaries because of its convenience and cleanliness in operation, also it is more readily adapted to automatic and remote control, particularly in the boiler-house.

(4) More efficient from the point of view of continuous operation, resulting in a reduction of station performance costs. It is also uniformly efficient, since lack of maintenance does not affect the efficiency of electrical plant, although it would tend to reduce the reliability.

(5) With the robust design of motors the question of reliability is amply catered for. Auxiliary transformers, switchgear and cables which play such an important part in the sub-division of the various electrical services are also very reliable.

(6) Requires less maintenance and is simpler to operate; it also improves the physical design and operation of the station by reducing the amount of auxiliary high-pressure steam and exhaust lines.

(7) Smoothness and comparative silence in operation, and although not so important, is a desirable feature.

A battery for driving auxiliary plant is out of the question for a large station in view of the capital expenditure and the space required to house it.

Where D.C. is required recourse may be made to :—

(1) Rotary convertors or motor convertors.
(2) Induction motor generators.
(3) Synchronous motor generators.
(4) Rectifiers.

Flashing over on the commutator, stability under fluctuating load conditions and parallel operation have to be considered.

Having adopted electrical drive it will be necessary to decide whether A.C. or D.C. shall be used, or where two auxiliaries are used, *e.g.* extraction pumps, vent fans, etc., if one A.C. and one D.C. drive should be provided. The system adopted in one station is such that the A.C. motor-driven extraction pump operates continuously on a 6,000 kW. set. In the event of failure of A.C. supply, a D.C. motor-driven pump which takes its supply from the station battery comes into operation. When the A.C. supply is restored the A.C. pump comes into service and the D.C. pump is shut down. A steam turbine-driven circulating water pump of 160 B.H.P. at 6,000 r.p.m. through reduction gear is used for starting up the plant when A.C. supply is not available and serves as a stand-by to the A.C. motor-driven pumps.

In one large station each circulating water pump is driven by a 1,200 B.H.P. A.C. motor above which is mounted a smaller D.C. motor, the respective motor shafts being connected through a coupling. In the event of breakdown of the main motor the smaller unit will drive the pump at reduced output.

The boiler feed pumps, circulating water pumps and certain other plant may be run independent of the main plant or at least a proportion depending on the station feed and circulating water systems. Separately driven steam feed pumps, steam circulating water pumps and electric pumps supplied from an auxiliary turbo-alternator are possible.

The circulating water pumps should maintain a supply of cooling water sufficient for safety at all times. Where stoker-fired boilers

are in use, particularly the retort type, it is necessary to maintain the water level in the drums, otherwise serious tube damage will result. It is impossible to damp or rake off the fires on the retort type, hence the importance of maintaining boiler water level.

Essential and Non-essential Auxiliaries. Having tentatively decided on the method of drive to be adopted, it is necessary to group the auxiliaries and pay attention to detail in so far as the importance of the services bear to the main units.

The auxiliaries can be grouped into two

(1) Essential auxiliaries.
(2) Non-essential auxiliaries.

The first are those which must be kept in almost continuous service if the station is to maintain its output. The non-essential auxiliaries are those which can be taken out of service for appreciable periods.

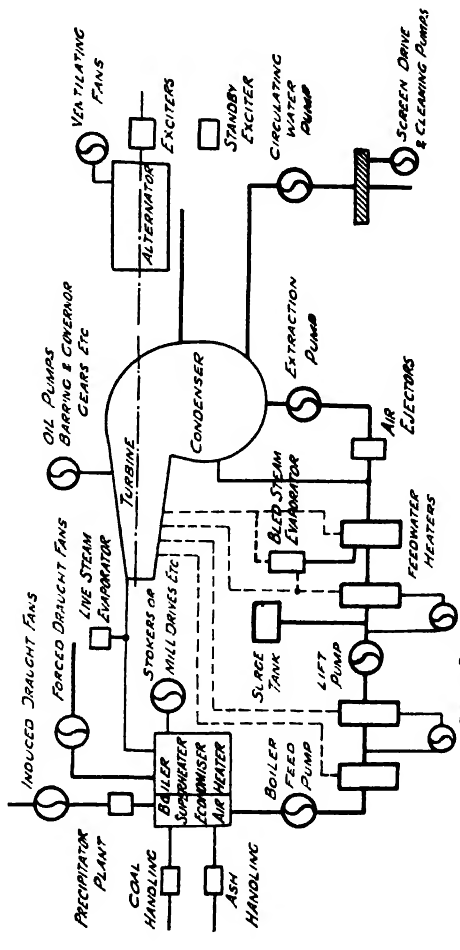


Fig. 493. Diagrammatic Lay-out of Principal Auxiliaries.

The auxiliaries in each class vary according to the method of boiler firing and the stand-by plant installed, and also local conditions.

Considering the boiler with the four methods of firing now in use :—

In all methods the forced and induced draught fans and boiler feed pumps are essential auxiliaries. The essential auxiliaries with Stoker firing—Stoker drives.

Pulverised Fuel (Central System)—Primary Air Fans and Pulverised Fuel Feeders.

Pulverised Fuel (Unit System)—Pulverising Mills and Feeders.

Oil Fuel—Fuel oil pumps and associated auxiliaries.

The essential auxiliaries for a turbo-alternator are the circulating water pump, extraction pump, auxiliary oil pump and possibly the screen drives, also the ventilating fans for the alternator if separate fans are fitted. Circulating water pump failure causes a drop in vacuum and is usually more serious where the piping and pump system is on the unit principle. The failure of the extraction pump also results in drop of vacuum due to the cessation of the steam air ejector in addition to the flooding of the condenser air suction. The gland leak off heaters and gland steam condensers which may be fitted on H.P. turbine glands are also without water.

Lighting and switchgear tripping circuits are essential services. The importance of a reliable lighting supply is obvious, for should failure coincide with station trouble the demoralising effect that follows total darkness aggravates the inconvenience. The tripping circuits should be taken directly from the station battery as an interruption or undue lowering of the voltage on these circuits for even 30 to 60 seconds may lead to serious trouble.

Non-essential auxiliaries include coal and ash-handling plants, service pumps, oil pumps, barring gear, exciter field rheostats, lifts, cranes, valves, governor control, evaporator auxiliaries, etc.

Generally the turbine auxiliaries are of greater importance than the individual boiler auxiliaries for it is usual to provide two to four boilers for each turbine and should one fail it is possible to continue at full load by operating the remaining boilers at their continuous rating. There has been a trend towards one boiler per turbine, in which case the boiler auxiliaries are equally as important as those of the turbine.

Auxiliary Power Supplies. The size and types of turbine and boiler plants, and in no small measure the site conditions, will determine the amount of power required. In addition to providing for conditions of normal operation, the problem of getting a station into service after a complete shut-down must be borne in mind. An alternative supply is in most cases absolutely essential when electrically-driven auxiliaries are exclusively employed. The alternative supply should receive full consideration as to its suitability under certain conditions of operation, some of which are :—

(1) Starting up the first set of a new station and also any subsequent sets

(2) The operation during all conditions from no-load to full-load.

(3) The shutting down of any section or sections of the station distribution systems—both main and auxiliary.

(4) The possibility of faults on the station and system networks and the results thereof.

It should be unnecessary to parallel the reserve supply during emergency conditions for mistakes are possible at such times. The use of a certain proportion of steam-driven auxiliaries is sound. Figs. 494 to 498 show some methods of affording these supplies.

With stations interconnected and operating in parallel an internal breakdown is unlikely to coincide with a system failure. This is a reasonable assumption but it should be remembered that failure of one station may be responsible for the failure of neighbouring stations and the network generally. The use of overhead lines for interconnection is quite safe in peace time, but during war and particularly since the advent of intensive aerial warfare the possibility of barrage balloons being scattered round a city or industrial area must be allowed for.

During sudden changes of weather, *e.g.*, a rise in wind, it is quite possible for some of these balloons to break away and foul the overhead lines, resulting in loss of interconnection. Lightning may also cause similar inconvenience by firing the balloons. Fugitive balloons have been responsible for a number of interruptions over fairly wide areas. Where such air-raid precautions are taken it is advisable to cover the local demand of the station by keeping one or more turbo-alternators on the bus-bars. The import and/or export conditions together with the local demand have to be taken into consideration before a final operation programme is formulated. By careful choice of balloon position some degree of safeguarding against fouling may be achieved, *e.g.*, by placing them on the leeward side of the lines. A further precaution is to keep one line "dead," and if fouling has taken place, to make investigations as soon as circumstances permit before closing up. In this way a considerable saving in time and materials is effected, although just how far this can be carried out will depend upon local conditions.

The point to be borne in mind is that so far as the supply of electricity is concerned an essential auxiliary is just as important as a main unit, in fact main unit breakdown is probably more excusable in the eyes of a consumer. A good turbine has been occasionally condemned because of repeated failure of its main oil pump.

The chief systems of supply are :—

(1) Station or works transformers connected to main bus-bars either directly or by way of reactors.

(2) Unit transformers connected to the alternator terminals.

(3) House service alternators mechanically coupled to the main alternators.

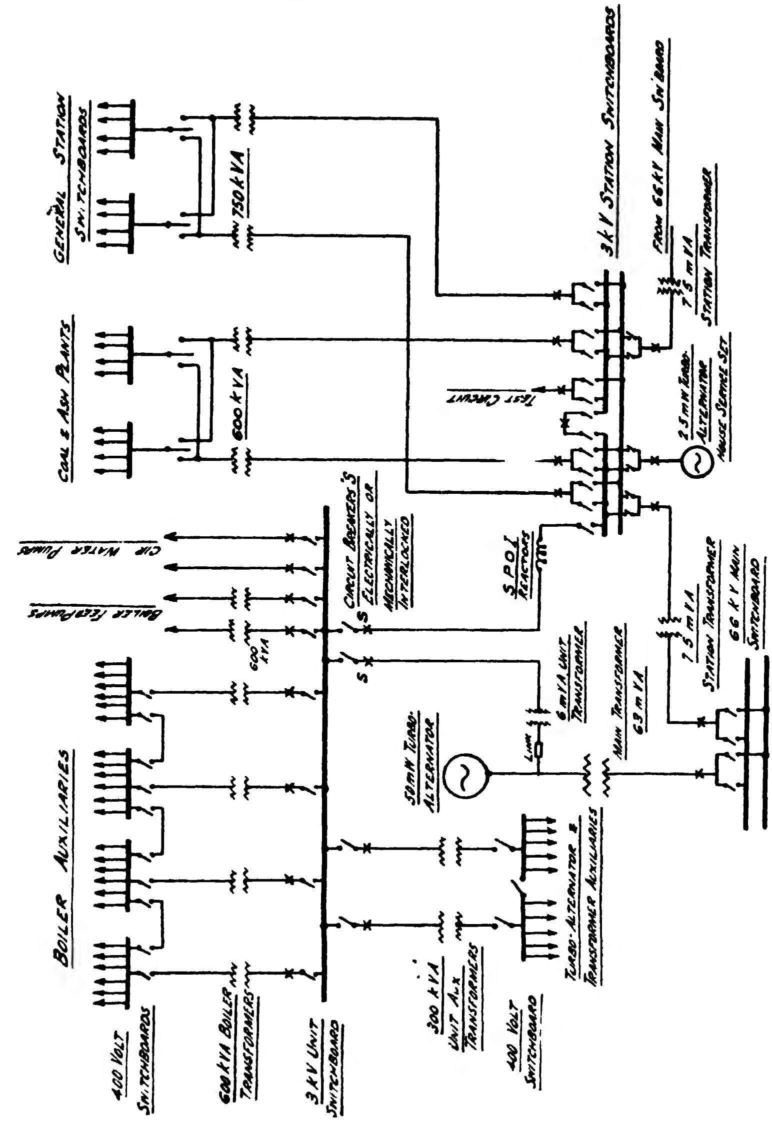


Fig. 494. Unit System of Auxiliary Supplies.

(4) House service alternators driven by independent prime movers.

(5) Tertiary windings on main transformers.

(6) Direct-current auxiliaries from rotary convertors, motor convertors, motor generators or rectifiers with stand-by storage battery.

(7) A combination of (1), (2) and (3) or (4).

(8) A combination of (1) and (6).

The possibility of resorting to a combination of any of these systems will depend on existing conditions and the trend of future developments. The layout of the electrical distribution scheme for the supply and control of the auxiliaries should be designed with the following features in view :—

(1) To limit the effect of failure of any individual piece of apparatus on the complete plant to a minimum.

(2) To arrange the distribution system so that failure of an individual feeder will not unduly affect the essential auxiliaries.

(3) To provide a duplicate supply where economical and practicable.

(4) To protect the plant against faulty operation by the inclusion of protective and interlocking devices.

The use of D.C. or A.C. for essential auxiliaries demands careful consideration and each station must be considered in relation to the system of which it forms part, and account taken of all operating conditions.

The division of the plant and the question of reliability are to a great extent determined by the complete rigidity of connection which A.C. introduces. It may be argued that the bus-bars are divided into sections and outside supplies provided but the disadvantage of a network disturbance being carried to every part of the station system has to be allowed for.

(1) **Station or Works Transformers.** This is the most common system which is straightforward and reliable and by duplicating the transformers it is possible to supply them from sections of the main bus-bars which have physical and electrical separation. Isolators on the low-tension sides of the transformers and a section isolator complete the electrical separation throughout. If the secondary sides of the transformers are high voltage and the switchgear rupturing capacity is over 150 MVA it is justifiable to include physical separation. By taking supply from the main bus-bars use is made of the most efficient source of power, *i.e.*, the main turbo-alternators. The primary switchgear is of the same rupturing capacity as the main units, thus entailing more expense. A further

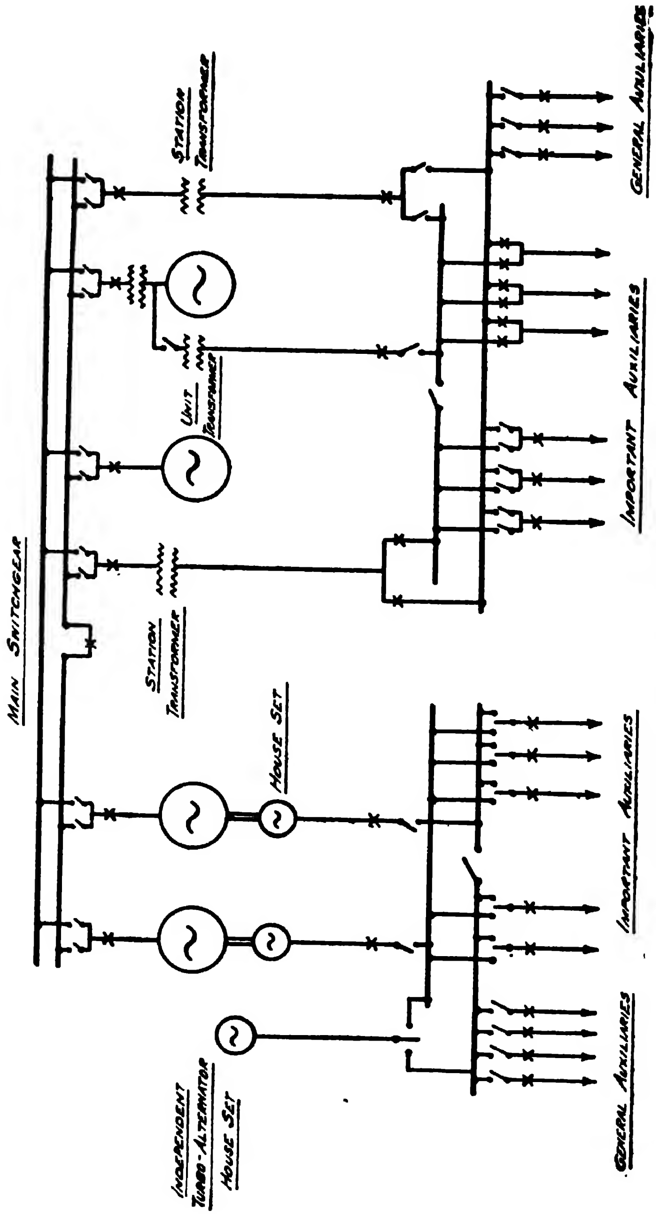


Fig. 495. Alternative Auxiliary Supplies.

disadvantage is that it is affected by voltage and frequency disturbances on the system.

Transformers are cheap and may be housed, or placed outdoors as site conditions permit. The secondary sides can be paralleled if required, and a faulty transformer can be disconnected without affecting the remaining equipment.

(2) **Unit Transformers.** A separate transformer, termed a unit transformer, is provided for each alternator which enables the power to be sub-divided at a more suitable voltage for auxiliary services.

The unit transformer is popular since it provides a simple and flexible auxiliary power supply when the alternator circuit-breakers are arranged to trip on overcurrent, for it keeps the auxiliaries running. Many alternators require no such protection except for back-up, the main circuit-breaker opening only on internal faults and the unit transformer breaker opening and stopping the auxiliaries. When the main circuit-breaker opens on stand-by overcurrent or earth leakage protection the unit transformer, field suppression and neutral earthing circuit-breakers remain closed.

When a turbo-alternator is run up, the power for the auxiliaries is taken from a house set or a station transformer, the latter taking supply from the main bus-bars.

After the auxiliaries are up to speed and the main set is on the bars they are changed over to the unit transformer for normal working until the set is shut down, when they are transferred to the station board. This enables the auxiliaries to run as long as may be necessary whilst the main set is slowing down.

The switchgear controlling the two supplies is fitted with mechanical or electrical interlocks to prevent paralleling.

Where starters have no-volt coils, the shutting down of the auxiliaries is avoided when changing over from the station transformer to the unit transformer, and Fig. 506 illustrates one arrangement. The unit switchboard has a bus section for splitting the bus-bars and the auxiliaries are sub-divided. This allows of the following operations when running up the set :—

Unit transformer circuit-breaker and bus-section circuit-breaker are both open. Close station transformer (starting) circuit-breaker and run up extraction and circulating water pumps on that side. Shut down auxiliaries on station transformer side. When the load is such that a second circulating water pump is required close bus-section circuit-breaker. To avoid short-circuiting bus-bar reactors it is necessary to ensure that both circuit-breakers are not closed

together. This may be prevented by fitting an auxiliary trip coil to the bus-section circuit-breaker, operated from the D.C. trip circuit and small auxiliary switches to each circuit-breaker (unit and station transformer) operating lever, the switches being set to close slightly in advance of the circuit-breaker. Each auxiliary switch is connected to the trip circuit, the closing of which completes the circuit and operates bus-section trip coil.

A time delay of 50–60 cycles has been suggested when transferring station auxiliaries from one source of supply to another. Any

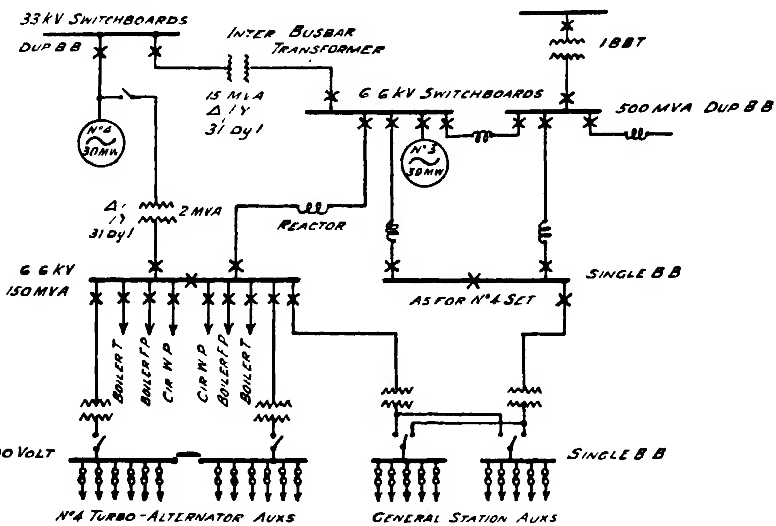


FIG. 496. Alternative Auxiliary Supplies.

shorter delay may result in high inrush currents while anything of the order of 10 to 12 seconds would interfere with overall operation of the plant.

On large sets it is usual to provide synchronising equipment for paralleling the unit transformer and alternative supplies (either *viâ* station transformer or reactor) and parallel operation of different sources of supply should be avoided. In the event of failure of one source, switches may be left closed which may lead to trouble in emergency and possibly aggravate the situation. In planning a distribution system all conditions of operation must be taken into consideration.

The unit transformer is a high efficiency source of power and has the advantage in that it is obtained without the use of a further

main circuit-breaker. The transformer may be connected solidly to the alternator terminals or through a non-automatic isolator.

A three-pole isolator on 33 kV. alternators necessitates a rather large cubicle, usually in three sections. Points worthy of attention are :—

(1) Possibility of back-feed from lower voltage side.
(2) Provision of insulated barriers between phases.
(3) Earthing contacts and earth bar to cater for (1).
(4) Cubicle doors to be fitted with locks and reinforced glass windows.

The short-circuit MVA available at this point makes it economically impracticable to include a circuit-breaker for the control of the transformer primary. In these circumstances it is necessary to ensure that a fault in the unit transformer or its connections shall open the alternator, unit transformer, field suppression and neutral earthing circuit-breakers. This is an undesirable feature introducing as it does an additional risk of interruption of the main supply.

(3) **House Service Alternator on Main Shaft.** This has the advantage that it makes use of the high thermal efficiency which can be reached on turbines of large output. The output varies considerably but shaft sets of 5,000 kW. are common. The heat consumption per unit of auxiliary power will be practically the same as the main set. The overall length of the complete unit is increased which necessitates a larger turbine house, thereby increasing the building costs. The mechanical reliability of the main set may also be affected.

A further disadvantage is that its output is not available until the main set has been run up to speed and put on the bars, and it cannot therefore form the only source of supply to the works auxiliary system. The supply from auxiliary shaft alternators cannot be synchronised with the supply from the main alternator except perhaps when the latter load is small to which it is mechanically coupled and the switchgear arrangement must be such as to make paralleling supplies impossible.

To carry load an alternator must shift its relative pole position (from position of synchronism at no load) forward by an angle sufficient to produce a resultant voltage between generated and applied voltage. As the house set is rigidly connected to the main set (it must also shift through the same mechanical angle) it follows that at the time of paralleling the main set, the house set cannot supply a voltage in exact opposition to the system voltage. If it is desired to parallel with a given load on the main set the rotor

of the house set must be relatively positioned that it lags behind the main set by an angle equal to the angular displacement caused by the load. At this load the house set can be paralleled since it generates a voltage in opposition to the line voltage. Paralleling of house sets is not recommended due to the possibility of shaft damage from surges likely to be set up.

The main and auxiliary alternators mounted on the same shaft must have equal load angles. The distribution of load between these two units therefore cannot be altered by external means but will depend upon the design characteristics. Both alternators could be designed so that the load of either is relative to its output, but difficulty would be experienced in synchronising the auxiliary alternator if this was tripped while the main set was on load.

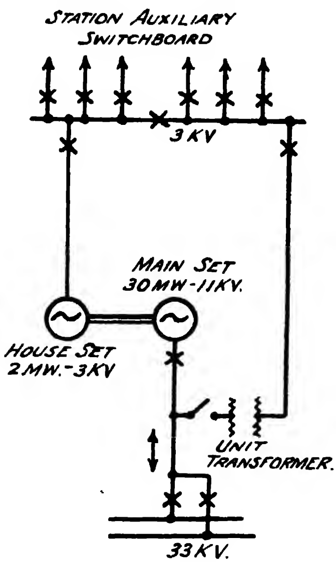


FIG. 497. Shaft House Set Supplies.

Interlocked circuit-breakers can be used but a fall in auxiliary bus-bar voltage might result due to greater inherent regulation of the alternator compared with a transformer. A double bus-bar arrangement avoids this difficulty. The auxiliary shaft alternator insures that the auxiliary power is not affected by system voltage disturbances but frequency changes may cause trouble. The cost is higher and the efficiency lower than that of transformers of equivalent output whilst the reliability of rotating plant may always be slightly inferior to that of static plant

The exciter voltage of a shaft-driven house set may lag considerably during the starting of very large auxiliary motors.

A shaft set is cheaper than an independent set, has greater mechanical stability and will hold its voltage and frequency at times when the main set is disconnected from the system, so keeping the auxiliaries running.

(4) **Independent House Service Alternators.** These provide complete independence and apart from being electrically separated, can, if desired, be given physical separation, although this would entail increased costs in building and interconnecting pipe-work, etc.

Speaking generally they are only used for stand-by service, in which case high efficiency is not of prime importance.

If used for regular supply of a large proportion of the auxiliary power requirements turbo-alternators up to 10,000 kW. can be built with a heat consumption not very much higher than that of the main sets. This fact, coupled with the absence of transformation losses, compensates for the somewhat higher capital cost per kW. of auxiliary power supply which is the case when house service turbo-alternators are employed.

In stations of very large capacity it appears justifiable to install independent house turbo-alternators even although inter-connection with other stations is available. They are independent of all main system disturbances, are simple and flexible. The protective equipment should provide for the possibility of overload in the event of trouble and so try to take the station load. The turbine output will of course limit the electrical load.

The use of house sets may entail additional attendants to ensure continuity of auxiliary supplies, but much will depend on the station capacity and layout.

Taking four large stations of between 200 MW and 400 MW capacity, the independent house service sets installed are :—

Station	(A)	2—	3,500 kW.	steam turbine-driven house sets.
,,	(B)	2—	2,500 ,,	,, ,, ,, ,, ,,
,,	(C)	1—	10,000 ,,	,, ,, ,, ,, ,,
,,	(D)	4—	7,000 ,,	,, ,, ,, ,, ,,
,,	(E)	1—	750 ,,	Diesel engine house set.
,,	(F)	1	1,100 ,,	,, ,, ,, ,,

It is usual for the house set to be driven by steam turbine since it is reasonable to assume that all the boiler plant will not be put out of commission in the event of a breakdown, together with the added advantage of making the station an "all-steam station" On the other hand consideration has been given to Diesel engines for auxiliary power supply. This seems to be very sound for both are about equal in reliability and maintenance charges, whilst there are no stand-by losses with oil engines and very quick starting is possible. This latter feature has been almost equalled by the steam turbine for sets of 3,000 kW. can be placed on the bars within six minutes. In one station a 1,000 kW. house service set operating at 3,000 r.p.m., is designed to give full output with the same steam conditions as the main sets equally well when the steam

pressure is reduced by 25 per cent. The turbine is non-condensing and exhausts at atmospheric pressure. The unit is designed for quick starting from cold and can be put on load up to its full rating in about three minutes. Another large station has a 5,000 kW. house set on each main unit and in addition an ultra-emergency house service set of 2,000 kW. capacity which is for use in only dire necessity and can be started up by pressing a button in the control room. The voltage of these sets is 3,300 volts.

The capital cost of Diesel plant is high so that the capacity should be kept within reasonable limits. This should normally be such as to permit running up under light load of two boilers and one main turbine. Small Diesel engine plants may be housed some consider-

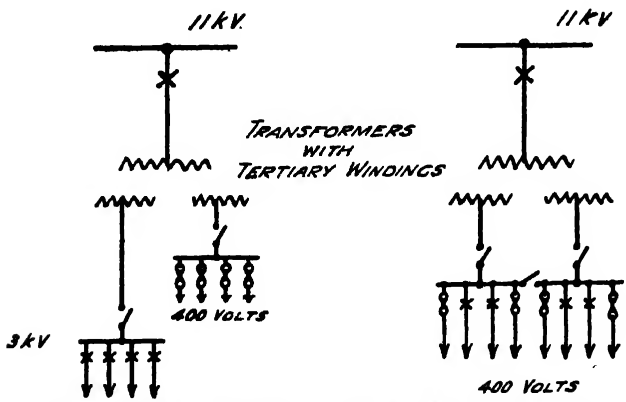


FIG. 498. Auxiliary Supplies from Tertiary Wound Transformers.

able distance from the main generating plant which is an advantage in the event of fires or other very abnormal conditions. They can also be arranged to maintain all emergency fire-fighting and control services without endangering the operatives. One recent 420 MW station has three Diesel-engine-driven fire pumps each with a capacity of 1,000 g.p.m. at 100 lb. per sq. in. discharge pressure. Automatic fire-fighting equipment on the turbine oil-purification plant and on the main and auxiliary transformers works in conjunction with these fire pumps, two of which will always be on automatic starting and the third on manual control for fire-hydrant service around the station. As it is desirable to test cables, switchgear, etc., before putting into service, the house set can be used for this purpose.

(5) **Tertiary Windings on Main Transformers.** This is similar to the first scheme, the difference being that separate auxiliary trans-

formers are dispensed with. The main transformers are provided with tertiary windings to which the works auxiliary switchboards are connected.

In one station each 35 MW alternator is connected directly to its 45 MVA tertiary wound star-delta-star transformer. This steps up the alternator voltage from 14·4 to 140 kV. for connection to the transmission system. The third winding on the transformer gives a supply at 22 kV. for transmission purposes and also for station auxiliary services. When an alternator is out of commission the latter services can be fed from either of the transmission systems. The larger motors operate at 3,000 volts and the smaller ones at 400 volts, a 5 MVA transformer stepping-down from the 22 kV supply for each alternator at 3,000 volts. The auxiliary service bus-bars are normally operated separately but a bus-coupler is provided to close automatically should one of the transformers fail. Each transformer has sufficient capacity to supply the essential auxiliaries of both units. The 400-volt motors are supplied from three separate bus-bars which can be inter-connected through section switches. These also are taken from two 750 kVA transformers connected to the 3,000-volt bus-bars.

Tertiary windings, apart from being included on the main step-up transformers, may be provided on the usual works auxiliary transformers if sub-division of auxiliaries is required at, say, 400 and 3,000 volts.

The use of transformers with two 50 per cent. secondaries is an economical arrangement where about 2,500 kVA or smaller banks are required and the reactance between sections of bus-bars is low.

(6) **Direct Current Auxiliaries.** Although the trend in power-station design has been away from the extensive use of D.C. drives for auxiliaries, a number of stations are still with some D.C. plant.

Much will depend on local conditions, the nature of existing plant and probable future extensions if the station is not a new one. In stations which have been added to from time to time it is possible that the older plant will have been working with D.C. auxiliary drives. A large storage battery may be installed, which probably served for traction purposes and makes quite a good reserve up to certain limits. A storage battery, if installed for auxiliary power alone, would be a most expensive proposition, due to the size required. The inclusion of a stand-by battery of sufficient capacity to supply the whole of the essential auxiliaries of the largest

set for at least one hour is the nearest approach to 100 per cent. security. The normal D.C. supply would be taken from the main bus-bars which receive their supply from either rotary or motor converters, motor generators or rectifiers with combined manual and automatic change-over switches. The change-over switches bring the battery on to the main bus-bars in the event of a predetermined drop in volts and it is usually necessary to introduce a time delay to prevent the two switches being closed on the bus-bars simultaneously.

A battery is very useful in the event of complete station shut-down. It is a source of power which is immediately available, and if a high discharge rate is possible it is useful for giving supply to even some of the larger essential auxiliaries. A battery is necessary to maintain a certain amount of light and also supply tripping circuits. There are cases where each essential auxiliary has an A.C. drive for normal service, but is duplicated by D.C. drive for emergency conditions. D.C. drives are still favoured by some engineers where speed regulation is essential, such as for boiler draught fans, mill feeders and particularly in pulverised fuel installations. This system of supply is unaffected by main network disturbances.

In one large station two 250-kW. motor converter sets are installed to the D.C. apparatus and for charging the main battery in conjunction with a reversible booster. A 50 kW. induction motor generator and reversible booster is used for charging the switchgear operating battery.

Another station has two 500 kW motor generators to provide D.C. for the more important auxiliaries and an automatic battery booster.

(7) **and** (8) **Combination of Systems.** These combinations will be readily understood and the accompanying diagrams illustrate examples met with in practice.

Abnormal Conditions of Operation. Having outlined some of the systems of auxiliary power supply it is possible to examine the alternative abnormal conditions of operation which may arise.

The first, and, no doubt, the most serious is that of complete shut-down on both the main and auxiliary power systems. In such circumstances systems 1 to 3 and 5 are useless in so far as re-establishing auxiliary power is concerned. The seventh system would cater for this condition providing it included a house set in accordance with the fourth system. The only two systems capable of meeting such an emergency would be 4 and 6, the latter being the better if the storage battery capacity is adequate.

In the majority of modern stations the fourth system with turbine drive would no doubt be the only one to which recourse would be made. Even then it must be possible to ensure that certain other conditions exist, *e.g.*,

(*a*) That the boilers be stoker-fired and have a reasonably large water capacity relative to their steaming rate.

(*b*) Circulating water and extraction pumps of sufficient capacity must have a D.C. or steam drive if a condensing turbine is used.

(*c*) If possible, the house service turbine should be designed for quick starting from cold at reduced steam pressure. There is no difficulty with sets up to 5,000 kW. of standard design.

If a large capacity battery is available, say, 1,200 ampere-hour or more, then pulverised fuel boilers may be entertained.

Pulverised fuel boilers employing the central system would require D.C. drives for the draught plant, feeders and primary air fans. If the unit system is adopted then at least one mill must have a D.C. drive in addition to the draught plant. If the shut down is due to an electrical disturbance and the steam range is still charged there will be sufficient steam to start and run a reasonable sized house set even with pulverised fuel boilers. If all pulveriser and boiler fan motors are supplied from the bus-bars through transformers or direct by means of motor or rotary converters, etc., external interruption would cause stoppage of these motors resulting in a fall of steam pressure so rapid that load-shedding could not save the station from falling out of synchronism with the network.

No difficulties should arise in the boiler house if chain grate stokers are installed and the fan supplies fail, as such conditions will assist in keeping the steam pressure down whilst the standby steam-driven feed pumps will maintain safe water level. The boiler safety valves will inevitably blow for a short time.

With retort-type stokers under similar circumstances some considerable time would elapse before steam pressure falls off.

Other failures to be kept in mind are those of individual transformers and switchboards and a thorough investigation as to the load conditions in such circumstances is desirable.

If a medium size turbo-alternator is available in the station this may be arranged for exhausting to the atmosphere in emergency, but such conditions of operation are not to be recommended for prolonged periods. It should be remembered that at low loads the turbine steam consumption is very high. Speaking generally, it is usually impossible to run a set of, say, over 2,000 kW. to atmosphere

on account of the greatly increased steam consumption and consequent lowering of the boiler pressure, together with the rapid increase in temperature at the low-pressure end of the turbine and condenser.

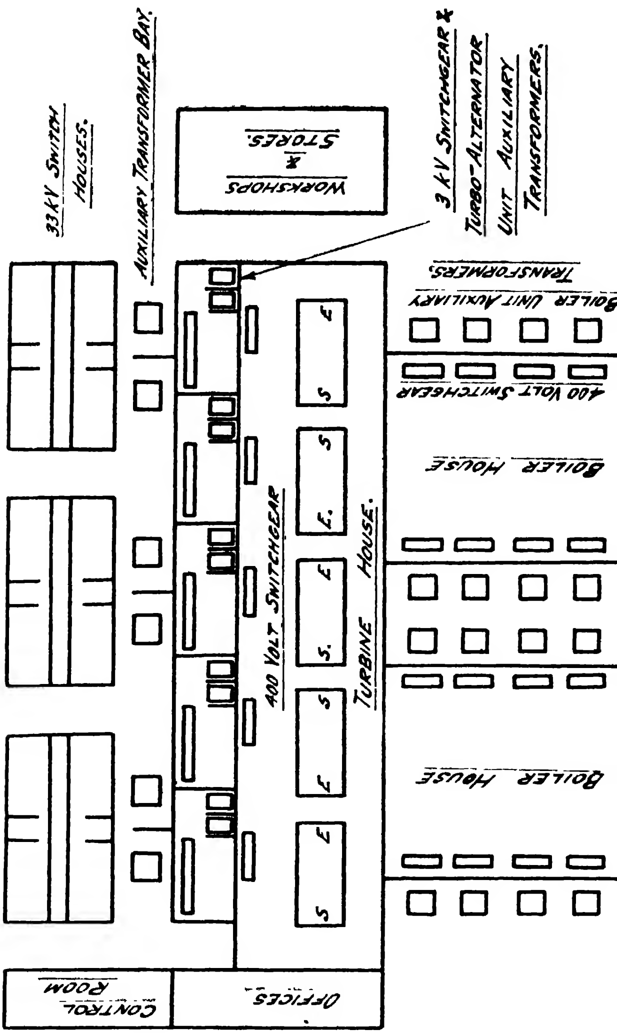


FIG. 499. Suggested layout of Switchgear and Transformers.

There is a great risk of uneven expansion with consequent distortion or cracking of the rotor wheels and L.P. casing. Similar trouble is liable to take place on the condenser if of cast iron, and in this case there is further danger in that if the going over to atmosphere is

due to failure of circulating water supply and the latter is restored when the condenser shell and tubes have warmed up the sudden cooling may cause cracking. Fracture of the metal at the low-pressure end is also possible due to the sudden cooling which takes place when vacuum temperature is reached. It is advisable to open the condenser end doors and allow the machine to cool down gradually.

Where the boiler plant has all D.C. drives and the turbo-alternator plant A.C. drives, it must be possible to give an emergency supply to both. This can be effected if a battery of reasonable capacity is installed together with a rotary converter arranged for inverted running. The converter is started up from the battery and run for such a period until a main turbine is able to go on the bars. The converter will be required to supply a circulating water pump, extraction pump, and possibly one alternator ventilating fan. The inclusion of a steam-feed pump will relieve the battery and converter and is always worthy of consideration.

When an independent house set is installed, particularly a Diesel engine drive, there should be no cause for anxiety as to the conditions after a complete shut down. The probability of a shut down for a prolonged period is similar to the condition of starting up an entirely new station and it is here that the Diesel engine drive has the advantage. The "direct-on-line" switching of very large motors will have to be borne in mind when fixing the house set output. An under-frequency relay can be included to cut-out a house set and the auxiliary supplies from the rest of the system and thus ensure full voltage and frequency being maintained to the auxiliaries.

From the foregoing notes it will be appreciated that the operating conditions under abnormal circumstances are of primary importance and all possible care is necessary if satisfactory use is to be made of the alternative schemes provided. It is advisable to draw up operation instructions covering every alternative and in order to keep in touch with correct procedure periodic revision with spare shifts is helpful, although the actual operating conditions will depend much on the station loading and plant available.

Auxiliary Switchgear, Transformers and Cables. With the sources of auxiliary power fixed it now remains for the ratings of the switchgear, transformers and cables to be determined.

The switchgear-rupturing and current-carrying capacities will depend primarily on the systems of supply adopted. If reactors

or transformers are included between the main and auxiliary switchboards, which is the general practice, then the reactance of these units will to a great extent determine the fault MVA. The method of estimating this fault MVA is outlined under "Transformers and Reactors," Chapter XIII. The current-carrying

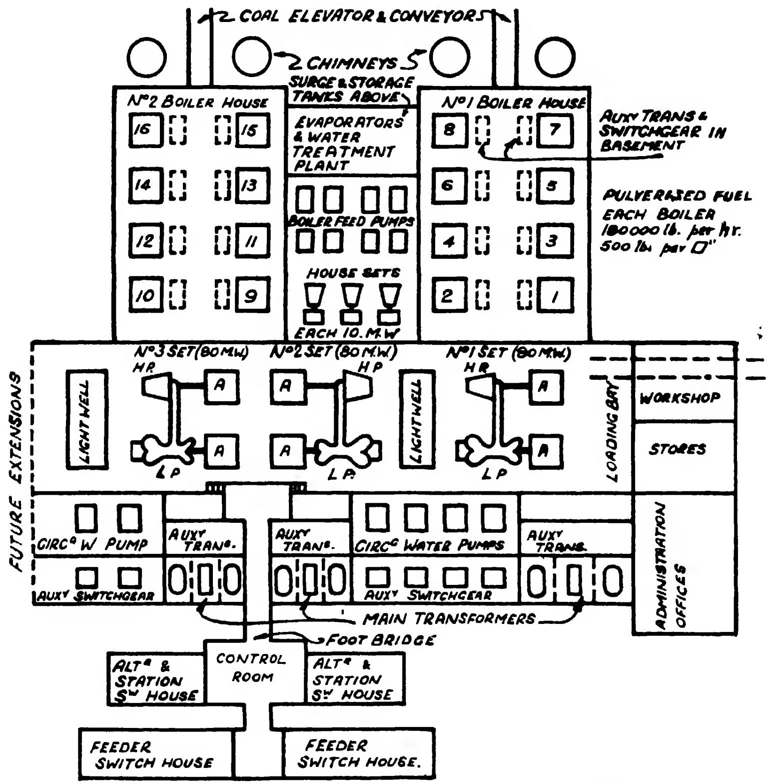


FIG. 500. Layout of Plant and Buildings for 350 MW Station.

capacity will be fixed by the load to be carried, but it is usual to install the nearest standard circuit breakers.

The transformer loading will also vary according to the system of supply provided. A unit transformer may be designed to carry the total auxiliary load of its corresponding turbo-alternator and boiler plant plus an allowance to permit another turbo-alternator to be run up. An alternative to a unit transformer is the use of two auxiliary transformers supplied from a main switchboard. These

transformers are usually arranged to give supply to the auxiliaries of one main turbo-alternator. Station auxiliary transformers will supply all general turbine house auxiliaries.

The boiler and boiler-house transformers vary considerably in loadings, and in large capacity stations it is usual to provide one transformer per boiler. In medium-sized stations two boilers per transformer may be reasonable and a saving in higher-voltage switchgear is effected. Interconnecting cabling arrangements may be included on the low voltage side to give an alternative supply. The boiler-house transformers will generally serve coal and ash-handling plants in addition to general auxiliaries.

The cable sizes should be chosen on a basis of fault MVA., as well as upon load-carrying capacity if mechanical and thermal damage is to be eliminated. The number of sizes should be kept to a minimum for no real advantage is gained by having numerous sizes of very small cables. Where heavy sections are necessary the use of two cables per phase of a standard cable is preferable.

The use of copper-clad cables for the smaller low and medium voltage services is increasing in popularity, particularly where the ambient temperature is high or in damp situations.

The chapters dealing with switchgear, transformers and cables outline in general the requirements for both main and auxiliary plant.

Layout. In discussing the various sections of main plant in other chapters reference is also made to the auxiliary plant associated with it.

Where possible the auxiliary transformers and switchboards should be as near to the centre of gravity of the load as practicable. The various sub-divisions of auxiliary switchgear and transforming plant are indicated on the diagrams. The physical layout of these items will depend primarily on the station layout, and the principle followed will be similar to those for the main plant. To reduce cabling the transformers should be placed near the switchboards which they serve. These sub-stations should be physically isolated from other plant which may give trouble or be endangered by faults on the sub-station plant. Figs. 499 to 501 show various layouts.

Fireproof barriers are justifiable to ensure physical separation of transformers and switchboards. Particular attention should be paid to the arrangements made for cabling so that the incoming and outgoing power and control cables can be marshalled in an orderly and safe manner.

The provision of alternative supplies must be kept in mind so that full use may be made of available plant in an emergency. It should be possible to obtain access to every circuit-breaker at reasonable intervals without the necessity for closing down large sections of plant. In this respect interconnection of pipework and steam plant facilitates matters on the electrical system.

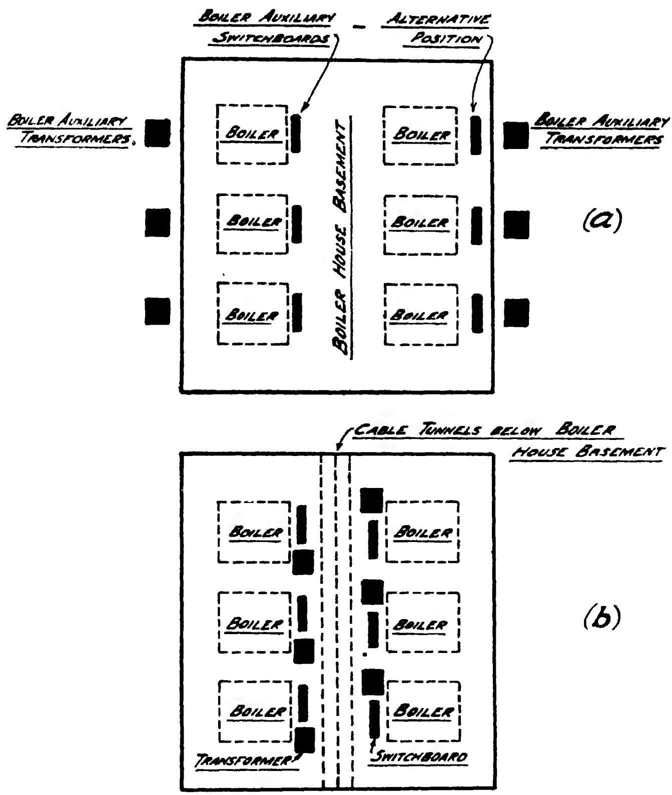


Fig. 501. Layout of Boiler Transformers and Switchboards.

The question of metering must also be considered and in most cases it will be possible to reduce the meters required to be regularly logged to a reasonable number. Whether the output of the unit or house service transformer is included in the alternator meter depends on the position of the meter transformers for the set. If the current transformers are included in the neutral ends of the alternator windings the auxiliaries are metered on the alternator meter and

should therefore be subtracted on the alternator summator meter. Should the metering current transformers be installed in the main circuit-breaker the output of the unit or house service transformer will not be metered by the alternator meter. Similarly, if an emergency house service set is provided solely for works auxiliaries its output will not be included in alternator meter and it must not be subtracted from the alternator summator.

The main works switchboards are usually arranged for remote control, the lower-voltage boards being manually operated. The switches controlling the main feeders to the boiler house and turbine house auxiliaries are often controlled from a board either in or close to the main control room so as to facilitate operation during emergency conditions. In some stations, a secondary control room or annexe has been provided for these works feeders. These switchboards may be placed in an annexe between the turbine and boiler houses which forms a convenient central position for grouping of equipment. In some cases the motor starting gear may also be grouped at this point as it provides central control, simplifies interlocking and facilitates maintenance. Before making a decision in this respect the requirements of the Factories Acts, 1937, 1948 should be considered.

The turbo-alternator and turbine house auxiliaries do not present any great difficulties, and the supply and control centres can usually be arranged to suit the various sections of plant.

The supply and control centres for the boiler auxiliaries may not be straightforward, for much will depend on whether a low or high level boiler fan layout is adopted. Whichever layout is used centralised control of the auxiliaries is often employed, the push-button controls being mounted on the instrument panels located on the operating floor. To comply with the Factories Acts additional " stop " buttons arranged for locking off should be placed near each auxiliary drive unless other means of isolation on the switchboard are provided and suitably placed. In choosing the positions of the various items of electrical plant and apparatus, particularly in the boiler house, care should be taken to ensure that they are not unduly exposed to heat, dust, steam and water pipes, etc., which to some extent are inseparable from the boiler house.

Unified Boiler Control. With this method of control it is usual for each boiler to have a motor-generator set connected to the fan, feed pump and stoker motors, the fields of the motors being supplied from the exciters coupled to the motor generator. The

ratios of the speeds are controlled by adjusting the field rheostats and the actual speeds fixed by the generator voltage. The generator fields are supplied from the exciter bus-bars and if it is desired to raise or lower the steam supply of the boiler, the field

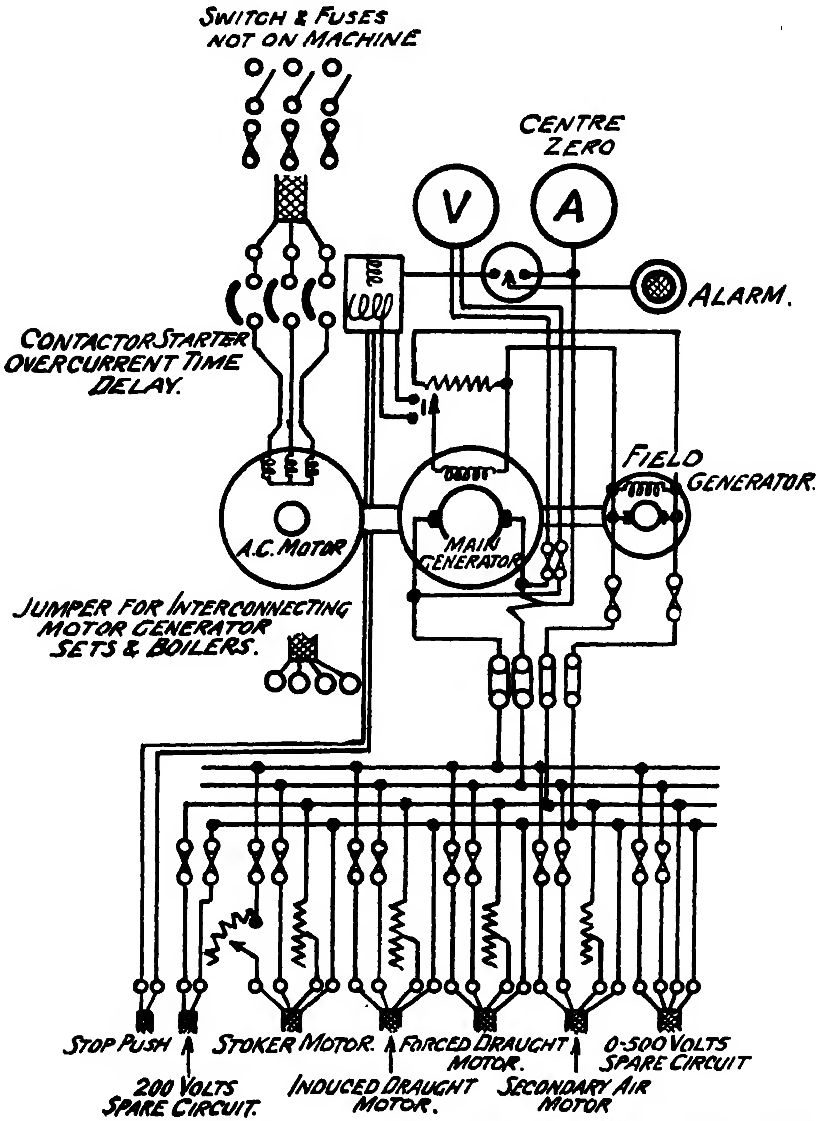


FIG. 502. Schematic Diagram for Unified Boiler Control. (Metropolitan-Vickers.)

rheostat of the generator is adjusted thereby altering the terminal voltage of the generator. The excitation busbars are fed from a small exciter connected to the station battery and complete control of the boiler output is obtained by adjusting the voltage of this small exciter (Fig. 502).

The operator can adjust the fans so that the furnace is burning with the best possible air and fuel conditions while the combustion engineer need only adjust the field rheostat on the generator to raise the steaming rate of the boiler. To raise the steam capacity of the boiler plant it is only necessary to raise the voltage on the excitation busbars. It is claimed that the auxiliary power consumption is much lower than other systems.

The auxiliary power consumption of a boiler in terms of boiler output may be summarised as follows :—

Mercury arc rectifier (with grid control) . .	1,270 lb. of steam generated per kW of auxiliary power used.	
Ward-Leonard . .	1,100 lb.	ditto
Average of other forms of boiler control . .	800 lb.	ditto

It is claimed that the auxiliary power consumption is much lower than other systems.

Automatic Boiler Control. Automatic control is now in general use for all large plants. The advantages claimed are :—

(1) A more constant pressure is maintained.
(2) A better efficiency of combustion, that is a better average of CO_2.
(3) An even distribution of load over the boilers.
(4) A slightly higher and more even temperature of the superheated steam.
(5) The possibility of carrying slightly higher peak loads.
(6) The possibility of carrying the normal loads with a minimum number of boilers.
(7) Greater flexibility of operation.

Automatic control systems have been developed chiefly in order to maintain load against demand, to prevent smoke, to increase boiler-house efficiencies, to carry out routine adjustments, and to provide inter-locking safeguards and self-acting cut-out devices. Another point is that labour can be conserved, but this is not the object of installing such systems. Automatic control should assist the boiler operatives to obtain better results by taking control of that part of their work which can be carried out by automatic apparatus

in an efficient and reliable manner. The operatives can therefore be engaged in more skilled occupations since the major portion of their work will be of a technical nature demanding a higher grade of

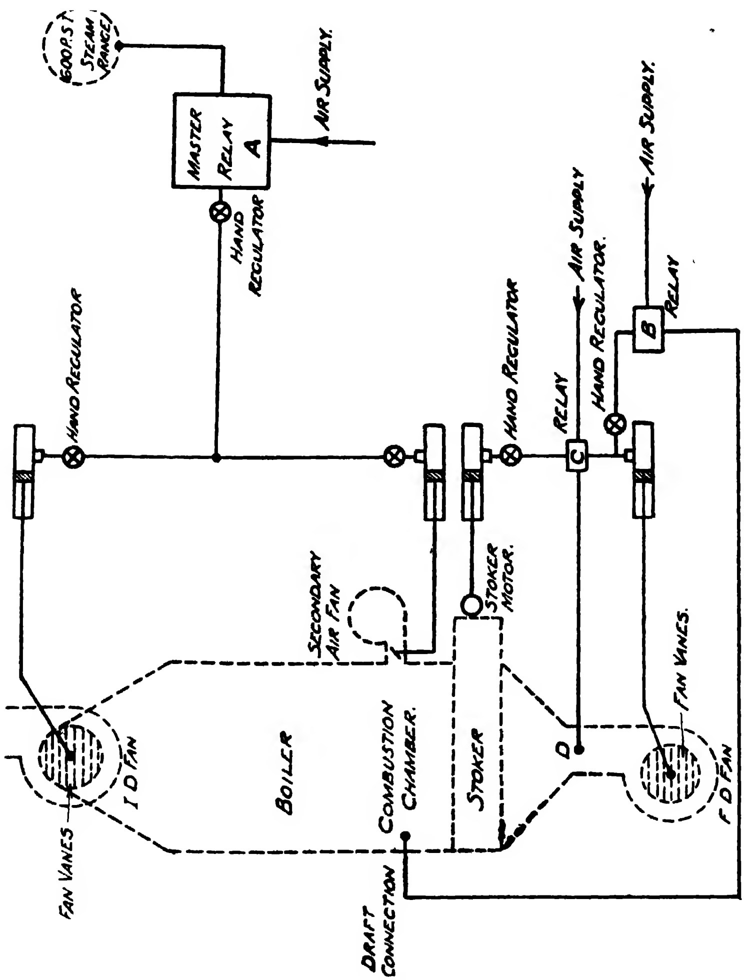


FIG. 503. Automatic Combustion Control.

operator. The conditions to be regulated in order to effect a change in the rate of combustion are draught, fuel supply and air supply.

The draught and air supply depend on the fans, and may be regulated either by dampers, vanes or by the speed of the fans, or both. The fuel supply has to be regulated in accordance with the method of firing employed.

Hagan System of Automatic Combustion Control. The operation of the system, Fig. 503, is dependent upon and follows the control of the master relay " A," which is sensitive to small variations in steam pressure and is coupled to the 600 p.s.i. range. Taking the case of a falling pressure, the drop in pressure causes relay " A " to operate the Servo-motor coupled to the vanes of the induced draught fan, causing this to open slightly and at the same time the secondary air fan damper is opened a proportionate amount. Following the readjustment of the induced draught, the stabilised condition in the combustion chamber is upset, and this in its turn causes relay " B " to alter the position of the forced draught fan Servo-motor, thus adjusting the position of the forced draught fan vanes, until the stabilised condition in the combustion chamber is re-established. This alteration causes more air to flow past the pitot tube " D," which operates relay " C " causing the stoker motor to speed up a proportionate amount, and feeding the extra quantity of fuel into the furnace. A rising pressure is the reverse of the above process. Each Servo-motor has a hand adjustment which allows its action to be advanced or retarded in comparison with the rest of the system. The master relay " A " has a hand control which allows for manual control of the whole system, that is to say, the system can be advanced or retarded in comparison with the steam action on relay " A." Each boiler has a sub-master hand control whereby the load on that boiler may be made to exceed or lag behind the load on the other boilers under the same master relay. Each Servo-motor has an adjusting arrangement termed an " angling " bar, which is shaped by experiment to ensure that the characteristics of each Servo-motor correspond to those of the others and also to the fan or motor characteristics. A compressed air supply is necessary for this system.

Hagan System of Reducing Valve and Temperature Control. This arrangement, Fig. 504, is designed to control the opening of the reducing valve and at the same time maintain correct pressure on both steam systems.

" A " is the 600 p.s.i. relay (referred to as H.P.).

" B " is a similar relay on the 200 p.s.i. system (referred to as L.P.).

" C " is a relay which reverses the impulses supplied to it.

" D " is a relay which averages the demands made on it by both systems, and passes the result on to the Servó-motor which actuates the reducing valve itself.

Assuming the pressure rises in the L.P. system, then relay " B " will reduce the output of the L.P. boilers and at the same time will bias relay " A " in favour of a reduction of pressure on the H.P. system. Relay " A " then increases the pressure on the Servo-motors on the H.P. boilers, causing these Servo-motors to close

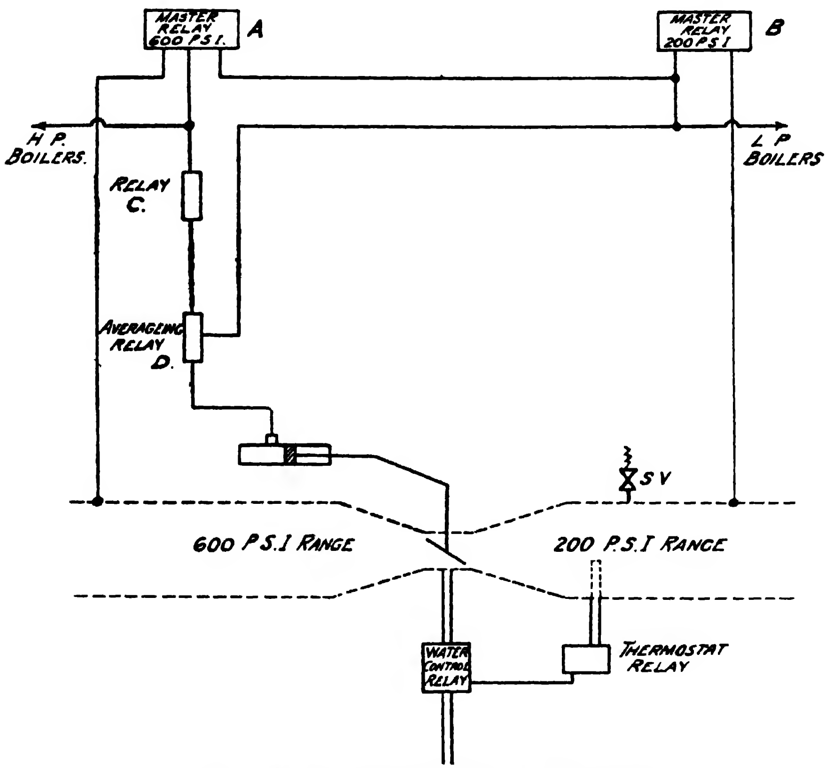


FIG. 504. Reducing Valve and Temperature Control.

down slightly and thus commencing to reduce the steam output on the H.P. system. Relay " C " reverses these impulses, and this reverse impulse tends to close the reducing valve, but the impulse from " C " and the impulse from " B " are both taken to the averaging relay " D " which passes on to the Servo-motor the average of these two impulses. The function of the averaging relay " D " becomes more apparent if a falling (or rising) pressure on both systems simultaneously is considered. Taking the case of an equal fall on both systems, then relay " B " will call for the reducing

valve to open but relay " A " will call for it to close, and providing these two demands are equal, no impulse is transmitted to the Servo-motor, but an impulse has been sent out to both the L.P. and H.P. systems calling for more steam. Should, however, one system be falling faster than the other, then the averaging relay " D " will operate the reducing valve in favour of the system in the greater difficulty. The averaging relay " D " is provided with a hand control which allows a bias to be imposed upon it in favour of whichever way is desired, that is to say, it is possible to maintain approximately continuous output on the H.P. plant and to allow the L.P. pressure to vary, or it is possible to impose such a bias that the L.P. plant will maintain constant pressure while the H.P. may vary. This can be done only within reasonable limits.

De-superheating. The de-superheating of any steam which passes through the reducing valve is carried out by means of a thermostatic relay inserted in the L.P. side of the valve. This relay sends the required impulses to a water controlled relay which controls the amount of water injected into the throat of the reducing valve, and is able to control the temperature by this method within very close limits.

Auxiliary Groups. When considering the auxiliary plant they can be sub-divided into the various sections of main plant with which they are associated. Figs 505–511 show some methods of giving supplies to the various auxiliaries.

In speaking of auxiliaries it is understood that they are required to be driven by either electric motor, steam turbine or some other form of prime mover and not items of plant which are commonly

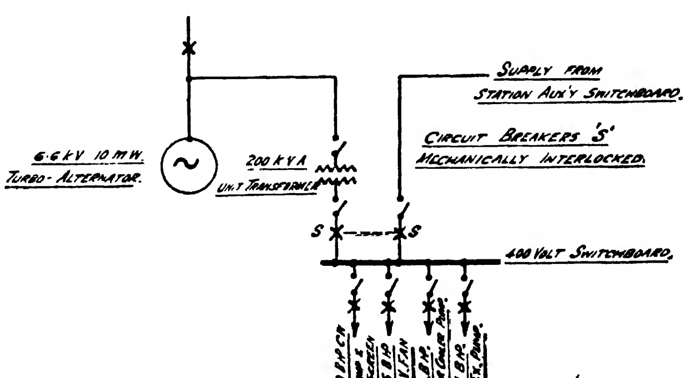


FIG. 505. Auxiliary Supplies for 10 MW Turbo-alternator.

termed auxiliaries, *e.g.*, coolers, ejectors, heaters, etc. The auxiliary plant may be grouped into the following sections :—

Boiler Auxiliaries.

It is advisable to sub-divide this section into Stoker, Pulverised Fuel, and Oil Fuel boilers.

Stoker.

Feed pumps.
Forced draught fans.
Induced draught fans.
Secondary air fans.
Stoker drive.
Hydraulic couplings and vane controls for draught fans.
Grit re-firing fans.
Air pre-heaters and valve drives and in the case of Retort Stokers ash crushers would be required.
Soot blowers.

Pulverised Fuel.

Feed pumps.
Forced draught fans.
Induced draught fans.
Hydraulic couplings and vane controls for draught fans.
Pulverising mills and exhausters.
Mill feeders.
Electrostatic precipitators and Valve drives, and in the case of a Central System, Primary Air Fans, Exhausters, Fuel Conveyors and Fuel Feeders would be required. Air heaters and soot blowers, etc.

Oil Fuel.

The usual auxiliaries are required with oil equipment replacing coal handling, etc.

The largest powered and most important boiler auxiliary is the feed pump. The general practice is to design a feed pump to deal with the total steam requirements of the corresponding turbine, *e.g.*, assuming an overall steam consumption of 10 lb. per kW. hour, a 30 MW set would have a boiler-feed pump capable of dealing with at least 330,000 lb. of water per hour. In some cases booster pumps have been included.

Oil lighting-up equipment for pulverised fuel will usually include oil pumps and probably an air compressor. The importance of this equipment will be appreciated when it is realised that without it the boiler plant is almost useless. Mention was made of the equip-

ment under Boiler Plant, in Volume 1, but a few further particulars are now given. Duplicate pumps are sometimes included, one being connected to the battery for emergency service and the other to the A.C. distribution board. The fuel oil in the storage tanks may be heated by hot-water coils, the temperature of the water being

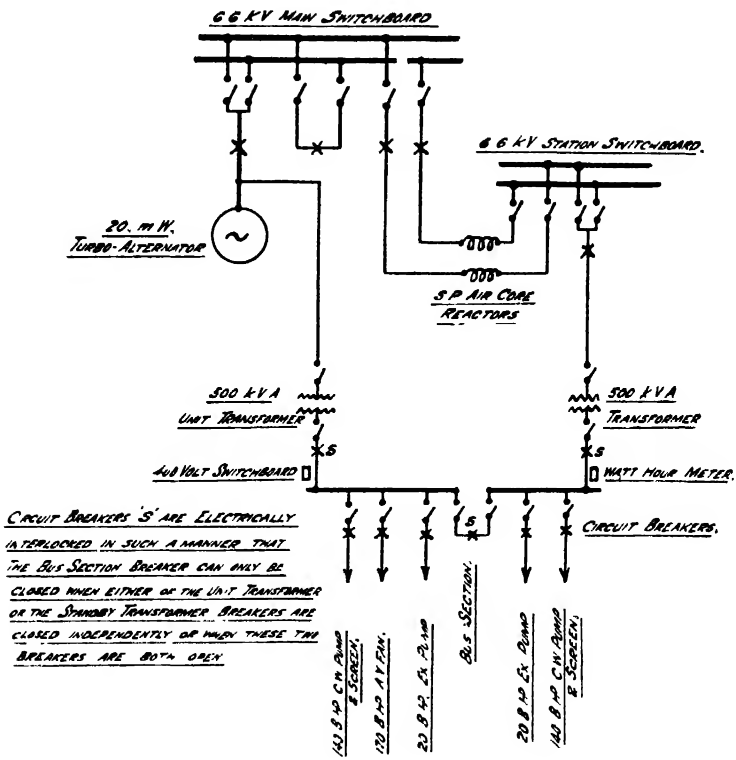


FIG. 506. Auxiliary Supplies for 20 MW Turbo-alternator.

thermostatically controlled by the oil pump. An isolating switch may be provided in the thermostatic circuit for use during the warmer periods when the fuel oil temperature is high enough for efficient combustion. A temperature indicator can be mounted on the boiler instrument panel to show the temperature of the oil at the bottom of the tanks.

Electrical operation of soot blowers is now usual and brings about a considerable saving in cleaning time, especially on very large boiler units.

Turbine.

Circulating water pumps.
Extraction pumps (condensate).
Governor control or speeder gear.
Circulating water screens and cleaning pumps.
Valve drive, evaporator sludge and distillate pumps.

Alternator.

Exciters.
Ventilating fans.
Exciter field rheostat.

The following auxiliaries are common to both :—

Barring or turning gear.
High pressure oil pump.
Emergency and auxiliary oil pumps.
Oil purifier.

Where a step-up transformer is associated with the turbo-alternator the additional auxiliaries are :—

Oil pumps and air blowers.

Coal-handling Plant.

Wagon tipplers.
Elevators.
Skip hoists and feeders.
Conveyors.
Capstans.
Cranes, telphers, etc.

Ash-handling and Dust Extraction Plants.

Conveyors.
Elevators.
Pumps.
Telphers.
Exhausters.

General Station Auxiliaries. The principal items are :—

Cranes, passenger and goods lifts, roller shutters.

Air Compressors. An air compressor service is usually provided to serve the following : automatic boiler controls, general cleaning, condenser cleaning and soot blowing.

Water and fire service pumps.

Workshop machines and equipment.

Water-treatment Plant.

The equipment required for such a plant will depend to a large

extent on local conditions, and may include a central evaporating plant.

Raw Water Pumps, Softened Water Pumps, Sludge Pumps, Stirring Gear, Distillate Pumps, Spray Pumps, etc.

Switchhouses.

Cranes, Trucks, Motor Generators, Boosters, Oil Pumps and Purifier.

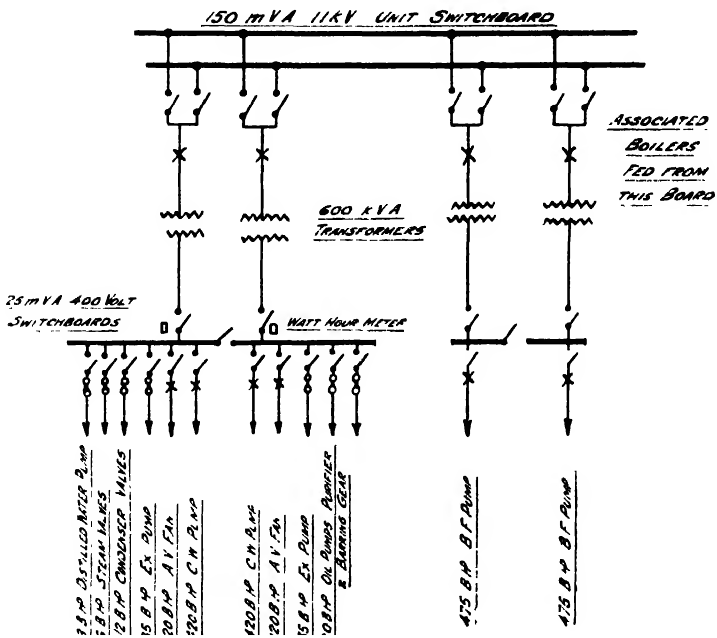


FIG. 507. Auxiliary Supplies for 30 MW Turbo-alternator.

Almost every drive in a power station is suited to electrical operation. For pulverised fuel installations it is sometimes the practice to use only electric pumps since a failure of feed water is not nearly so serious as in the case of chain grate or retort type stokers, where low water level may result in burning of tubes. Steam boiler-fed pumps are still employed as a stand-by and appear to be favoured by station staffs since they provide increased security in cases of electrical failures. Duplicate fire-service pumps are occasionally arranged for steam turbine operation.

Feed Pumps. In some stations it is the practice to keep the steam-feed pumps trailing, arrangements being made for bringing them automatically into service in case of electric pump failure.

The feed-water pressure in the system will fall when the electric pumps fail and this is made use of to operate an automatic steam valve on the steam pump. Difficulties have been experienced in running steam and electric feed pumps in parallel owing to their different characteristics. Such difference is overcome by fitting an oil relay gear which acts on the governor of the steam pump to ensure that the pressure-output characteristic of the steam unit is similar to that of the electric pumps. The advantage of keeping the steam-feed pumps turning is that they are warmed and ready for service in the shortest possible time. If the pumps are standing with steam up to the valve there is a possibility of the valve gear sticking, resulting in failure to start automatically when required. Care should always be taken to ensure that the pumps are tried for correct operation at frequent intervals and the valve gear, etc., maintained in good order. Another point of importance concerning these pumps—in the event of failure of the boiler non-return valves to hold or function correctly the feed range pressure is maintained at boiler pressure and in this case the automatic valves on the steam pumps will not operate. Cases are also on record where the feed pump non-return valve has failed to close on loss of suction, causing excessive pressure on the low-pressure heaters and pipework. Similar conditions may arise where a non-return valve leaks during shut-down period or in some layouts if a suction line isolating valve is closed first. To avoid damage, relief valves may be fitted although small valves are not capable of relieving the pressure to any great extent. Another method of overcoming this danger is to extend a branch of the feed suction line to a height just above the surge tank into which it is turned. The ingress of air must, however, be guarded against. With two or more pumps trailing in parallel it is almost impossible to arrange all automatic valves to act simultaneously. This introduces a further complication in that if one valve operates before the remainder a rise in feed water pressure will result and the other pumps will fail to come into service. Automatic valves may give trouble due to the metal rings seizing in the grooves and a method of overcoming this is to use red fibre hydraulic cup packing. Boiler-feed pumps are usually of the rotary type and a standard arrangement appears to favour one electric and one steam turbine-driven pump for a group of boilers associated with one turbine. This duplication is essential to maintain continuity of supply to the boilers where an outage of one minute or even less would reduce

the water to a dangerous level. In certain stations the operating conditions are such that a number of boilers may work on light duty for considerable periods. To cater for these conditions it is usual to install a small-capacity pump, probably about half-full load. This ensures efficient running and eliminates excessive throttling on the boiler valves. There is much to be said for having all the feed pumps steam-driven. With this exception the fewer direct steam-driven auxiliaries the better, not only from the maintenance and repair point of view, but also on account of the corrosion and deterioration which may take place in the casings due to leaking

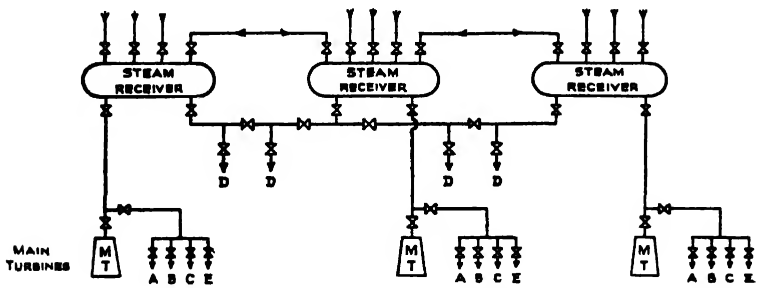


FIG. 508. Steam Supplies to Auxiliaries.

A. Auxiliary Oil Pump. B. Air Ejector, Main.
C. Air Ejector, Booster. D. Boiler Feed Pump.
E. Steam to Turbine Glands.

valves when shut down. A number of stations have all steam feed pumps which have proved suitable in all respects. The following figures refer to pumps of each class supplying feed water to boilers operating at 625 p.s.i.

Turbo Pumps—30 lb. of water delivered per lb. of superheated steam used.

Electric Pumps—1,000 lb. of water delivered per hour per kW.

Boiler Pressure	Pump Motor B.H.P.	Lb. of Water per Hour
625 p.s.i	475	300,000
300 ,, ...	250	330,000

Steam Supply to Auxiliaries. The only units required to be steam driven are boiler-feed pumps, emergency oil pumps, fire-service water pumps and occasionally the extraction pumps. Small

turbines are suitable for operation at the high pressures and temperatures now used and very few failures are recorded. An alternative is to use bled steam from the main turbine. Apart from the question of stand-by service the trend is to dispense with all steam-driven auxiliaries. To augment the feed heating system and conserve condensate large turbine-driven pumps exhaust into a feed heater. The advantages and disadvantages of using steam-driven auxiliaries have already been mentioned. The speeds of the steam turbines usually vary between 5,000 and 6,000 r.p.m.

For large stations justifying high capacity pumps of 500,000 lb. per hour and over, back pressure turbine drives through reduction gearing and operating at 1,500 r.p.m. are met with. The efficiency of back-pressure turbines is quite good and recovery of heat from the exhaust steam is possible.

The boiler-feed pumps and fire-service pumps are usually supplied direct from a main steam receiver so that steam is available at all times providing at least one boiler is working (Fig. 508).

The emergency oil pump, extraction pump and similar unit services are taken off the steam pipe to the main turbine. The air ejectors of the booster and main types are important auxiliaries. They are reliable and apart from very low steam pressures, give but little trouble. The main ejectors depend for their operation on the condensate extraction pump so that it is essential to have at least one pump always in service.

The pipe diagrams included in Chapter VIII, Vol. 1, dealing with " Pipework " show the points of connection for various steam auxiliary plant.

Voltages of Auxiliaries. The choice of voltages to be adopted is very important for not only does it affect the motors and their associated control gear and cabling but has a decided bearing on the range of switchboards to be used. The chief advantage of high-voltage electrical auxiliaries is the reduction in the size of cables. The range of switchboards for auxiliary services is more significant as the station grows unless a complete re-arrangement of auxiliary supplies is introduced. Motors are in service operating at 6,600 volts. Even with the largest sizes of motors now contemplated there does not appear to be any justification for exceeding 3,000 volts. There are, however, certain instances where it may be reasonable to use 6,600 volts if the auxiliary supplies are suitably arranged. The voltages commonly used are 110, 240, 415 and 3,300 volts alternating current. Direct current motors up to 480 volts are adopted where

this supply is available. The advantages of using alternating current are :—

(1) The transformer capacity can be arranged to meet all auxiliary plant requirements.

(2) The motors and control gear are cheaper, simpler, generally more reliable and require less maintenance.

(3) Commutator motors may be used but are not to be recommended for pulverised fuel installations or coal and ash-handling plants unless special enclosures are adopted. Such motors have been used for draught plants on P.F. boilers and have given satisfactory service.

(4) Fractional horse-power alternating current motors have proved satisfactory and wherever possible are preferable.

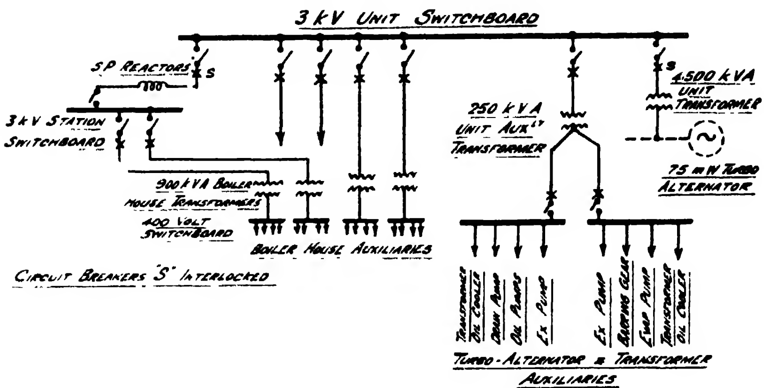


FIG. 509. Auxiliary Supplies for 75 MW Turbo-alternator.

Some usual figures are :—

400 B.H.P. and above	3,000/6,600 volts
Below 400 B.H.P.	400 volts.

There are certain drives where direct current motors still find favour, such as governor control, exciter field rheostats, valves, etc.

The standby or flushing auxiliary oil pump probably justifies a D.C. drive if both steam and electrical failures are to be guarded against. This pump can then be run under any condition and save the turbo-alternator bearings from damage.

Speaking generally, there is little to choose between the two classes of motors. The chief reason appears to be the difficulties and complications entailed by providing a special D.C. supply rather than any inherent defect of the D.C. motor. Further, by having A.C. and D.C. the number of spares which have to be carried are duplicated.

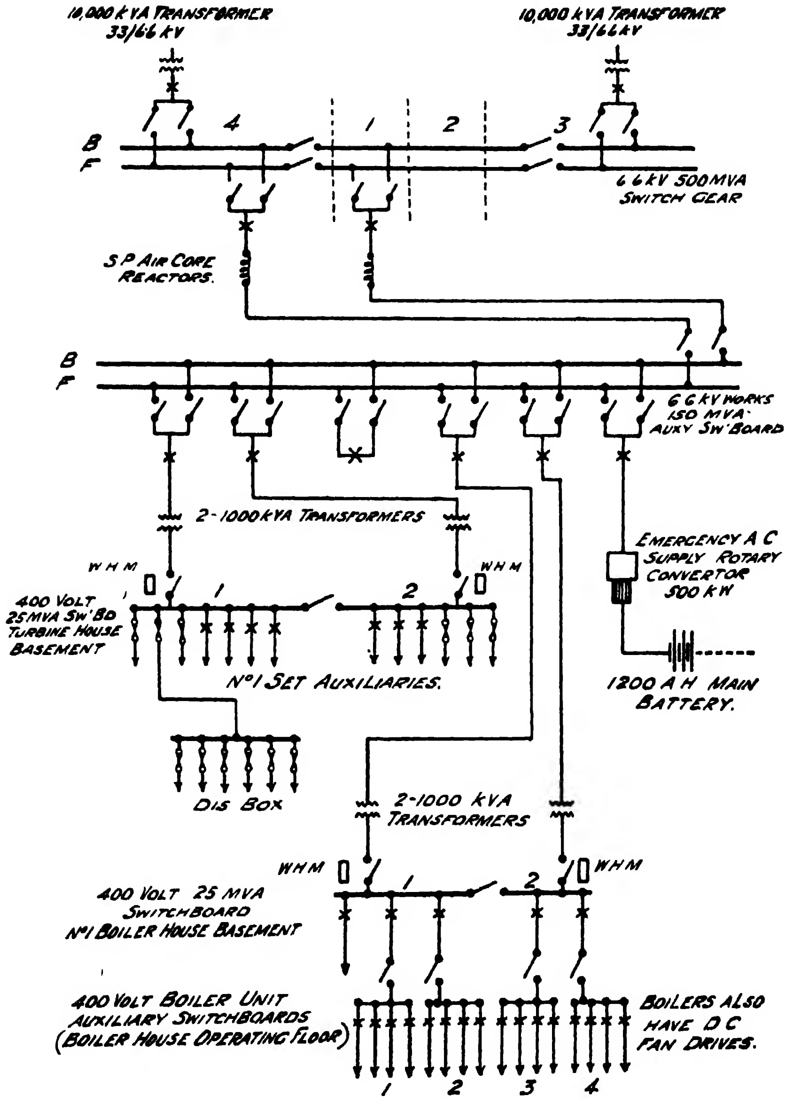


FIG. 510. Auxiliary Supplies for 30 MW. Turbo-Alternator and 4-130 k. lb. per hr. Boilers.

Types of Motors. The motors in general use are three-phase squirrel cage and slip ring types, the enclosures depending upon their location and service. The former are used where " direct on line "

starting is required. The rotors may have single, double or triple windings, the latter being used where the starting current has to be reduced to a minimum. Double and triple wound rotor machines have been used for conveyor and other similar drives where a large starting torque is required. They are simple and reliable and eliminate slip ring motors and contactor gear can be used where remote control is desirable. Tri-slot rotors have been used for boiler-feed and circulating water pump motors of 200 B.H.P. and upwards.

Three-phase squirrel-cage motors do not stall until a voltage of 60 to 66 per cent. of normal volts is reached.

For turbine house auxiliaries, screen-protected enclosures are invariably used although pipe-ventilated motors have been used for the alternator ventilating fan drives. Drip-proof enclosures may be used where leaky steam and water pipes are likely to give trouble.

The boiler-house auxiliaries usually require totally enclosed motors for almost every drive whilst special designs embodying air cooling are used for fan, mill, stoker and other drives. Where commutator motors (A.C. or D.C.) are used special armour-plate glass inspection windows are useful. The majority of motors are continuously rated, exceptions being crane, telpher, hoist and other intermittent working drives where half-hour and one-hour ratings are usual. All motors should be of ample output and this applies particularly to coal and ash plant drives where the loading conditions are so variable. Boiler-feed and circulating-water pumps are sometimes arranged for speed regulation to reduce the auxiliary power at low loads. To vary the speed of a slip-ring motor by the insertion of resistance in the rotor circuit is simple and not quite so wasteful in total power as would appear. In some stations the circulating water pumps are driven by slip-ring induction motors to good advantage. Take the case of one pump supplying two turbines ; when one turbine is working, resistance is inserted across the slip rings and the power falls from 140 to 80 kW. The reason is that the pipes are on a syphonic system and the total head is almost all due to water friction with the result that the power decreases as the cube of the speed (approx.), whilst the percentage of electrical loss only increases roughly with the slip. The chief disadvantage of driving pumps with A.C. motors connected to the main busbars is that the water delivery is reduced if the speed of the alternator should fall. This defect is aggravated if syphonic head is depended on, especially if the head is 20 to 25 ft. because, as the

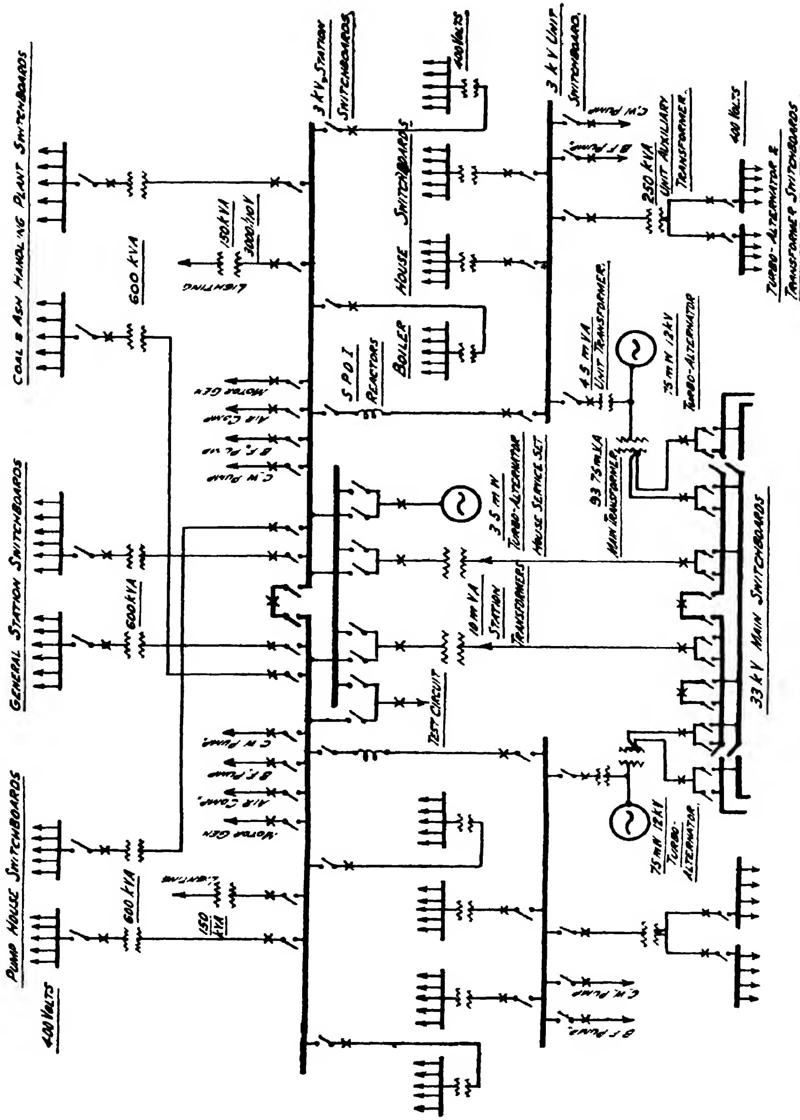


FIG. 511. Auxiliary Supplies for 2-75 MW. Turbo-alternators.

quantity of water is reduced, its temperature rises and the vapour given off reduces the syphonic head and diminishes still further the flow of water. The syphonic action is then liable to drop very quickly. Motors of the cascade type have been used, the main motor only operating when the plant is not working under syphonic conditions, the auxiliary motor coming into service when these conditions obtain. The effect of reduced speed would not be marked with cooling towers or river systems with open discharges. To allow for temperature differences in the river water over the year pump speed variation to the extent of some 100 r.p.m. is provided for by slip ring driving motors.

The speed of the boiler-feed pumps is usually about 3,000 r.p.m. and the rating up to 800 B.H.P., depending on the boiler and turbine plant supplied. Boiler feed pump power becomes a larger part of total auxiliary requirements at higher pressures and the pump motor size may well be limited by voltage drop during starting. The speed of the circulating water pumps should be chosen with care otherwise cavitation and other troubles may be experienced. For pumps up to 200 B.H.P. a speed of 740 r.p.m. appears to be suitable, but above this rating 585 r.p.m. appears to be the limit at which these should be operated.

A.C. commutator motors have been used for draught fans and stoker drives where wide ranges of speed are desired. An alternative is to use variable speed hydraulic couplings. Two-speed motors have been used for draught fan drives together with vane control on the fans. D.C. motors have also been used for forced, induced, secondary and primary air fans, also raw coal and pulverised fuel feeder drives where speed variation is necessary. As in foundry cranes, D.C. motors are considered to be much more satisfactory for this work, it being claimed that more delicate control can be obtained. A.C. motors for crane drives are giving satisfactory service.

The great disadvantage of A.C. motors is that in the event of loss of steam or system overloads resulting in a drop in speed of the main sets and fall of frequency, pump speeds are lowered at a time when they are most needed.

Motor Control Gear. The general practice is to arrange for direct switching of motors wherever possible as the auxiliary distribution scheme is simplified and the control boards and corresponding switchgear can be arranged to better advantage.

Care should always be taken to see that the control gear and its equipment comply in all respects with the Factories Acts, particu-

TABLE 66. *Auxiliary Plant Data*

Unit	Trend	Spare Plant	Speed Control	Remarks
Boiler-feed pumps	One electric pump per turbine.	One steam pump stand-by.	Constant speed motors.	In some cases speed control has been provided by hydraulic couplings. Steam pump comes into operation automatically on failure of electric pump.
Circulating water pumps.	Use of two pumps per condenser.	Ample reserve capacity in common systems.	Constant and variable speed motors.	"Direct on line" starting even in large motors. Vertical and horizontal pumps. 2–60 per cent. pumps if individual pumping system. Cascade motors sometimes used.
Extraction pumps	Electric drive standardised.	Duplicate pump provided.	Constant speed	Some have one D.C. pump and one A.C. pump or one A.C. pump and one steam turbine pump.
Alternator vent' fans.	Blowers on main shaft or separate motor-driven fans.	Motors usually liberally rated.	,,	Some have fans incorporated in alternator. Some have separate motor-driven fans. Some have blowers on main shaft.
Emergency oil pump.	Steam-turbine drive.	Motor-driven relay oil pump.	Steam regulator with by-pass valve.	In some cases a motor-driven pump has displaced the usual steam pump. D.C. drive sometimes adopted.
Oil pumps and barring gear.	All motor-driven	Hand oil pump and manual turning.	Constant speed	Transformer oil pumps and motors oil immersed to prevent ingress of air to oil system and causing Buchholz relay tripping. D.C. drive for flushing pump.
Governor control	A.C. motor-drive	Hand control at turbine.	,,	D.C. is still adopted on many installations.
C.W. screen drive	Independent drives	Screen chambers common.	Pole changing motors.	Constant and variable speed installations are used. Gear reduction. Two-speed motors are common.

Exciter field rheostat.	Motor-drive	Manual operation	Constant speed	D.C. motor usual.
Air ejectors	Steam ejectors	Duplicate ejector provided.	Constant speed for rotary ejectors.	A quick starting or booster ejector is usually provided.
Boiler draught fans.	Some form of speed control always provided.	Motors and fans usually liberally rated.	Speed control	Speed control by two-speed motors or A.C. commutator motors. Speed control by D.C. motors. Speed control by hydraulic couplings.
Stokers	Motor-drive	None	Speed control required	Chain grate stokers—constant speed motors with gear boxes. Retort stokers—A.C. commutator motors or hydraulic variable speed drive.
Pulverising mills	Motor-drive with two or three mills per boiler.	Sub-division of plant on unit system.	Constant and variable speed motors.	Wound rotor motors and A.C. commutator motors. "Direct on Line" starting also used.
Mill feeders	Separate motor-drive.	,,	Speed control	D.C. motors may be used.
Tipplers, hoists, conveyors.	Motor-drive	Bunkers provide ample storage.	Constant speed	Wound rotor motors, duplicate conveyors sometimes provided.
Ash pumps and telphers.	Motor-drive	Duplication provided.	,,	Pump motors "direct on line." Telphers and conveyors, wound rotor motors.
Service pumps	Motor-drive except fire pumps.	,,	,,	Fire pumps steam drive.

TABLE 67. *Electrically-Driven Auxiliaries. Installed Capacity*

	Turbo-Alternator M.C.R. Output	10 MW P.F.	20 MW P.F.	30 MW P.F.	50 MW P.F.	30 MW S.F.	50 MW S.F.	75 MW S.F
Auxiliaries	Boiler	750	1,500	2,200	3,800	1,550	2,700	3,400
	Coal and ash handling	60	60	100	130	120	130	180
	Circulating water system	120	280	410	600	410	600	1,000
	Turbo-alternator	50	210	320	620	320	620	150 *
	General station	80	80	150	200	150	200	250
	Total installed B.H.P.	1,060	2,130	3,180	5,350	2,550	3,250	4,980

Central and Unit System Boilers

Central System—60,000 lb per hr.				Unit System—130,000 lb. per hr.			
Service	No. Off	Motor	B.H.P.	Service	No. Off	Motor	B.H.P.
I.D. fan	1	D.C. compound	170	I.D. fan	1	D.C. compound	155
F.D. ,,	1	,,	100	F.D. ,,	1	,,	102
Primary air fan	1	,,	80	Electrostatic precipitator rapping drive	2	S.C.	2
Fuel feeder	2	,,	4	Ditto, rectifier drive	1	,, (syn.)	1·5
		Total	354			Total	263·5

* Turbo-blower on main shaft in place of motor-driven fans—S.F.—Stoker-fired Boilers. P.F.—Pulverised Fuel Boilers (Unit System).

Boiler feed pumps included with boiler auxiliaries.

With larger units it is justifiable to allow a greater margin of spare auxiliary plant. Other points to be taken into consideration are whether a river or cooling tower is used, and also the boiler pressure.

larly from the point of safety by suitably placed isolating apparatus.

The physical layout of the various auxiliaries should be considered before deciding on any particular distribution scheme.

In some cases it will be found possible to utilise the main distribution circuit-breakers as motor starters. The rupturing capacity of the various sections of control and switchgear will depend primarily on the transformers from which their supply is taken. Standard switchgear for 400-volt service is about 25 MVA rupturing capacity, although with air break switchgear it is possible to obtain equipment having a rating of 35 MVA. The overcurrent trip coils or current transformers may limit the MVA rating of switchgear and care

TABLE 68. *Installed B.H.P. for Turbo-Alternators*

30 MW. 3,000 R.P.M. Turbo-Alternators					
(*a*) Riverside Station			(*b*) Cooling Tower Station		
Service	No Off	B H P. Each	No. Off	B.H.P. Each	Remarks (*a* and *b*)
Circulating water pump	2	200	2	420	60 per cent. pumps.
Extraction pump .	2	30	2	35	100 ,, ,,
Alternator vent fan .	2	120	2	120	50 per cent. fans.
Boiler-feed pump .	2	250	2	475	100 per cent. pumps.
C.W. screen and cleaning pump.	1 1	2 4	— —	— —	
Barring gear . .	1	8/25	1	12/48	
Flushing oil pump .	1	$2\frac{1}{2}$	1	†35	† Stand-by aux. pump.
Jacking oil pump .	1	8	1	††$1\frac{1}{2}$	†† Alternator only.
Evaporator pumps .	1	6	1 1	6 3	
Oil purifier . .	1	$\frac{3}{4}$	1	3	
Governor control .	1	$\frac{1}{12}$	1	$\frac{1}{12}$	
Exciter rheostat .	1	$\frac{1}{8}$	1	$\frac{1}{8}$	
Total B.H.P. installed =		1,235		2,155	
B.H.P. normally running =		*935		⊙1,600	

* Steam pressure = 300 lb. per square inch.
⊙ ,, ,, = 620 ,, ,, ,, ,,

should be taken to see that the circuit-breakers on the main distribution boards are of the desired rating.

It is found convenient to use switch fuses for circuits up to 300 amps. and oil or air circuit-breakers above this figure. Switch-fuses may be obtained for 400 volt working at 25 MVA rating and have the advantage that under fault conditions they provide discrimination between the starters. The latter will not be required to operate under fault conditions, in which case the rating is not so important as protection is ensured. Fuses connected in series with circuit-breakers having overcurrent trips should have a greater time delay than the trips in order to allow the breaker to open first in the event of overcurrent. They only act as a back-up protection in case the breaker fails to open. In a number of other cases a delay in the clearing time is not desired, as for example when the circuit is not protected by an automatic trip device or when

TABLE 69. *Installed B.H.P. for Boilers*

187,500 lb. per hour M.C.R. 620 lb per square inch. 850° F. Stoker Fired (Retort).			130.000 lb per hour M.C.R 300 lb per square inch. 750° F. Pulverised Fuel (Unit System)		
Service	No. Off	B.H.P. Each	No. Off	B.H.P. Each	Remarks
I.D. fan . . .	†2	85/160	*1	115/155	† Low and high speed A.C. (Vane Control). * Variable speed D.C.
F.D. fan . . .	†2	45/110	*1	85/105	ditto.
Pulveriser mill . .	—	—	3	120	Slip ring.
Mill feeder . .	—	—	2	¾/1½	D.C. shunt.
Stoker . . .	1	3/10	—	—	A.C. commutator.
Ash crusher . .	2	10	—	—	
Air preheater . .	2	2	—	—	
Elect'c precipitator—rapping gear . .	—	—	2	1	
Elect'c precipitator—mech. rectifier drive	—	—	1	1½	
Total B.H.P. installed	=	550		625	

* The B.H.P. normally running will depend chiefly on the boiler load.
† The H.P. absorbed by the fans varies over a wide range.

the breaker has not the necessary capacity either to clear a severe fault or to close the circuit on short. In any such case it is desirable to have a rapid fuse which will blow before the first peak of the short-circuit current can develop in possibly less than one-quarter of a cycle with alternating current. If a starter is used in series with a circuit-breaker it is essential that it be of similar rupturing capacity unless a definite time limit relay is provided to ensure that the starter will not operate on fault.

For transformers up to 1,000 kVA. the percentage reactance is about five and for 400 volt services transformers of 1,000 kV.A. capacity are within the limit of 25 MVA switchgear. Where paralleling is necessary it may be advisable to increase the transformer reactance to keep within the safe limit of the switchgear rating.

So far as individual control gear is concerned there are a few cases where variable speed drives are used and these require special control apparatus in the form of rotor starters, two circuit-breaker arrangements, change-over contactors, auxiliary motors, induction regulator, electric couplings with electronic speed control, etc. The electric eddy-current coupling provides an infinitely variable speed from an A.C. supply. It has advantages of simplicity, ease of control and is adaptable to any type of motor. Motors approaching 800 B.H.P. have been arranged for direct on-line starting. Where two-speed motors are controlled by two circuit-breakers it is necessary to include a time lag device to prevent the motors being switched almost instantaneously from the high speed to low speed. With very high output motors a large reverse torque will have to be overcome. The use of choke coils in the stator leads arranged to come into circuit on change-over from high to low speed is an electrical method sometimes used, particularly on skip and other hoists.

Contactor starters are used when frequent starting and stopping is essential, whilst oil-immersed starters are suitable for all general purposes.

The auxiliary switchboards and control equipments for boiler-house service should be designed to prevent the ingress of dust and moisture. Where anthracite coal is used and the atmosphere is very humid trouble may be experienced from flash-overs on bus-bars in air unless precautions are taken. Tables 66 to 71 give auxiliary plant data. Typical motor and transformer data schedules are shown in Tables 72 and 73.

Speed Control by Hydraulic Couplings. These have been

TABLE 70. *Auxiliary Plant Loadings*

Station Capacity—80,000 kW. M.C.R. (River Station)	
Generated Load kW.	Station Auxiliary Load kW.
0—10,000	500
10,001—20,000	1,000
20,001—30,000	1,500
30,001—40,000	2,000
40,001—50,000	2,200
50,001—60,000	2,500
60,001—70,000	2,800
70,001—80,000	3,000

The plant installed consists of 2-10 MW sets and 2-30 MW sets. The actual loadings of auxiliary plant will vary according to the generated load and also local conditions.

TABLE 71. *Auxiliary Plant Loadings*

Station capacity—80,000 kW. (Cooling Tower station)	
Generated load kW.	Station auxiliary load kW.
0-10,000	900
10,001-20,000	1,800
20,001-30,000	2,300
30,001-40,000	3,000
40,001-50,000	3,800
50,001-60,000	4,500
60,001-70,000	5,000
70,001-80,000	5,400

TABLE 72. *Typical Motor Data Schedule*

Service.	Enclosure or Class.	No. off.	B.H.P.	Speed r.p.m	Voltage	Rating	Effy.	P.F.	Stator Current	Size and Type of Cables	Method of Starting	Con-tractor	Maker	Drawing Nos.			Remarks
														Con-tractor	Maker	Elec-tricity Dept.	

TABLE 73. *Typical Transformer Data Schedule*

Service	kV.A. Rating	Voltage-Phases		Connection		B.S.S. Symbol	Per cent. React-ance	Type of Voltage Control	Total Oil Galls.	Total Weight including Oil	Weight of Core and Wind-ings.	Type of Cooling	Drawing Nos.		Remarks
		H.V.	L.V.	H.V.	L.V.								Maker	Elec-tricity Dept.	

applied to draft fans, feed pumps, circulating water pumps, pulverisers, coal and ash conveyors, valves, and drag scrapers. Squirrel cage motors are used on all drives which simplifies control gear. Fan runners have increased life since their is no throttling of hot dust laden gases and power input is saved at reduced boiler loadings. Boiler feed pump outputs and pressures can be regulated to suit the boiler loads and here again power is saved and the feed-pipes are not subjected to unnecessary high pressures. In a circulating water system (river) where the water temperature and suction head vary, the most economical operating results can often be obtained by varying the pump speed. Fluid couplings also permit of the extension to cooling tower systems without the necessity for providing larger pumps or impellers of increased diameter. When used for drag line scrapers, clutch wear is reduced and the life of steel ropes is increased by reducing the peak stresses due to surging of the ropes.

Important Factors. The four factors to be considered in station auxiliaries are reliability, efficiency, simplicity and capital cost. Apart from the loss of prestige which a failure of supply occasions, there is another feature to be considered, namely, that of loss of revenue, which is considerable if a complete interruption of supply on the system occurs.

The problem of getting a station into commission after total shut-down is no light task, for the psychological aspect of such a failure is an important factor which has to be taken into consideration. In the event of failure, safety valves will be blowing, lighting probably reduced, and these combined with the uncertainty as to what has actually happened has for a short time a numbing effect on the operatives. Every auxiliary scheme, however well designed, remains a compromise, and the question as to what is and what is not to be installed must still remain a matter for individual judgment. The power station has become of such importance to the nation that its failure almost means a battle lost and it is essential that reliability of supply be maintained, even at the expense of efficiency. The latter is an important factor, contributing as it does to the saving of fuel and conservation of man-power and transport, but the effect of failure of supply needs no emphasis.

CHAPTER XVIII

ELECTRICAL PROTECTIVE EQUIPMENT

Many types of electrical protective equipment are used and it is not possible to give a detailed description of each. The protective equipment may be grouped under the following headings :—

(1) Alternators, (2) Transformers, (3) Reactors, (4) Cables, (5) Motors, (6) Switchgear.

The primary function of protective gear is to isolate faulty equipment with the minimum disturbance to the system. To minimise damage and disturbance due to a fault the essentials of a protective equipment are rapidity of operation combined with comparatively low settings. The ability to do this is termed discrimination which entails two essential characteristics, namely, operation and stability. Operation denotes the ability of the protective gear to isolate the protected unit when it is faulty. Stability is its ability to remain inoperative when the unit protected is healthy but carries the maximum short-circuit current which can flow into faulty equipment beyond it. This fault current is termed the "straight through current." The "stability ratio" is the ratio of the maximum through fault current at which the relay remains inoperative, to the minimum fault setting (or sensitivity). The sensitivity of a protective system may be defined as the minimum fault current to which the system is operative when a fault occurs within the protected zone. The primary fault current required to cause operation of the protective gear is termed the "fault setting," the secondary current required to flow through a protective relay to cause operation being known as the "relay setting." The time taken by the relay to operate is called the "time setting."

In a protective system where the stability is independent of protective systems or faults on other apparatus, and the operation only extends over the unit it protects is said to provide "unit protection." Examples of this are Merz-Price alternator and restricted earth leakage protective systems. A protective system, the stability of which is dependent upon the operation of protective systems of other apparatus and the operation of which extends over a range of protected or unprotected apparatus, is said to provide

"back-up protection." Examples of this are alternator overcurrent protection and high rupturing capacity fuses for motor circuits.

Protective equipment should be capable of repeated operation under abnormal conditions, be reliable, easy of adjustment, low cost, and be suitable for extension to existing systems without incurring much expense. Instability can only be caused by differences in the transformation characteristics of the transformers operating the protective system causing "out-of-balance" current to flow in the relay circuit resulting in false tripping. This out-of-balance is the difference in magnetising currents of the transformers and there are two methods of avoiding the false tripping likely to be caused by its presence :—

(1) By attempting to balance the transformers to obtain equal magnetising currents independent of their magnitude. This method depends upon obtaining absolute equality of two relatively large quantities in which a small percentage variation—due to such unknown factors as wave form, saturation, doubling effect, transient, etc., may produce sufficient out-of-balance current to cause false tripping, although under test conditions balance may be satisfactory.

(2) By reducing the magnetising current of the transformers to such a low value that although the percentage difference may be large—due to the causes mentioned above—in absolute value the magnetising currents will be less than the currents required to operate the relay. Although this method necessitates transformers of more liberal design, including larger cores, it has been adopted by several firms as standard practice on all transformers for protective systems. Such transformers are now designed so that under the worst operating conditions the magnetising current of any individual transformer does not exceed the current required to operate the relay. With this provision, even 100 per cent. variation in magnetising current will not cause false tripping. This method avoids :—(*a*) Pairing of transformers. (*b*) Biasing of relays. (*c*) Balancing of pilots. (*d*) The necessity of determining exactly the relay tapping points. If convenient, relays may be tapped off current transformer terminals, thus effecting considerable economy in pilot cables and the elimination of junction boxes.

Transformers of liberal design improve the stability as lower relay settings are possible without reducing the stability ratio. The bar primary current transformer is by nature of its construction more suitable to withstand the conditions set up during short-circuits than the wound type. Bar primary transformers are so constructed that there are no electro-mechanical forces tending to produce relative displacement of the windings. This type is regarded as ideal from the standpoint of thermal and mechanical security under primary short-circuit conditions, since its strength in both respects is almost

unlimited. Certain difficulties arise in both the bar and wound types with the lower ratios, below 100 amps. primary current. The output of the bar type is limited and the short-circuit capacity of the wound type may be inadequate. One solution is to use the bar primary type and to limit the V.A. burden by having separate transformers for instruments and relay operation. The minimum ratio for a practical design of the bar type appears to be 30/1 amp. and the output would be very small, probably just sufficient to operate a sensitive overcurrent relay or a low V.A. ammeter. Consequently with switchgear controlling low current circuits it may only be possible to provide a relay setting to cover fault conditions amounting to several times the full load current.

Current and voltage transformers are outlined in B.S.S. No. 81—1936. The overcurrent factor of a current transformer is given by $\frac{I_{RMS}}{I_{FL}}$,

e.g., with short circuit current of 15,000 amps. R.M.S. and a 100/5 C.T. O.C.F. $= \frac{15{,}000}{100} = 150$.

Two separate sets of current transformers are preferable, one for the operation of integrating meters and the other for instruments and relays. This not only simplifies design work and ensures satisfactory service for each specific duty but may result in economy of core material when a proportion of nickel-iron is used with silicon-iron stampings to obtain high-grade metering accuracy. For balanced protective systems such as Merz-Price circulating current and restricted earth leakage schemes, separate current transformers having cores entirely of silicon-iron are essential. The magnetising ampere turns required to excite the core of a current transformer are only a small proportion of the total primary ampere turns, usually less than 1 per cent. The vector difference of the primary ampere turns and magnetising ampere turns is balanced by the secondary ampere turns and when the secondary is opened the whole of the primary turns are available to magnetise the core and may set up an abnormally high flux density in it. This high flux density results in heating and abnormal secondary voltage with a high peak value and consequent danger to the transformer insulation. It may also leave the core permanently magnetised to a considerable extent, greatly reducing the permeability and increasing the ratio and phase angle of the transformer.

B.S.S. No. 81—1936 states : " It is important that the secondary

circuit of a current transformer should be kept closed when current is flowing in the primary, otherwise there may be induced in the secondary an extremely high e.m.f. The peak value of the voltage wave under these circumstances may be many times the R.M.S. value as measured by voltmeter and may even constitute a danger to life. Moreover, changes sufficient to affect the accuracy may be produced in the magnetic characteristics of the core."

Current transformers may be capable of being left open-circuited in the secondary with the primary circuit under full load without overheating or damage. This test imposes additional considerations in the design of transformers, the turns ratio being kept as low as possible, *e.g.*, where the primary is 1,500 amperes it is so arranged that the protection system has 5-ampere secondaries in order to keep the secondary voltage as low as possible. Substantial insulation between layers is provided and the turns are arranged in relation to each other to avoid unnecessary high voltages between adjacent conductors. Some manufacturers contend that no ill-effects have been observed on the iron used and no measurable change in magnetic characteristics when testing precision accuracy metering current transformers on open circuit. Where the maximum primary current does not exceed 1,200 amps. the secondaries may be short-circuited direct. If the primary current exceeds this value the secondaries should be short-circuited through a resistance (about 8 ohms), having a current capacity of some 25 amps. for about 3 secs.

If 5 amperes are to flow in the secondary when the primary has its full-rated current, the ratio of the secondary to the primary is fixed. For example, if 1,000 amperes pass through 1 turn (primary) the secondary turns will be $\frac{1{,}000 \times 1}{5} = 200$. In practice, probably 198 turns would be used, the difference being to compensate for primary magnetising ampere turns, resistance and leakage effects. One-ampere secondary current has been used where the distances between circuit-breakers and control panels and from the control panels to the alternator pits or step-up transformers are greater than usual. The general layout of major plant therefore affects the design of current transformers, etc.

To determine the correct connections for current transformers it is necessary to know the B.S.S. group reference to which the transformers will be connected. To facilitate tests of protective equipment test windings are included on the current transformers.

In this way it is not necessary to isolate a feeder, but should a feeder be isolated tests may still be carried out. Such test windings avoid disturbance of secondary connections, the making of connections for busbar spouts and does not require a spare alternator and busbar.

When an earthing or neutral point is required it is sometimes necessary to include a current transformer for either protective or indication purposes. The usual practice is to connect this current transformer on the earthing transformer or alternator side of the resistance, in which case the current transformer is subjected to a voltage of $E/\sqrt{3}$ on the occurrence of an earth fault. Under such circumstances the earth side of the resistance would be insulated for a lower voltage. When a liquid-type of earthing resistor is used the tank containing the electrolyte is connected direct to earth. If the earth plate should develop a high resistance the earth connections will be raised to a potential of line to earth voltage ($E/\sqrt{3}$).

Alternator Protection. Before outlining the protective systems employed for alternators, faults likely to be met with are enumerated: (1) Stator faults between phases and between phase and earth. (2) Failure of field and field suppression. (3) Failure of prime-mover. (4) Faulty synchronising. (5) Fire risks. (6) External faults.

There are other faults which may arise but experience has shown that the inclusion of special protective equipment to guard against such is unnecessary. Faults may occur between conductors of the same phase but such faults quickly develop into an earth fault and are covered by the standard protective gear. Stator windings with open circuit behave in a similar manner owing to the burning which accompanies the area at the rupturing point. Figs. 512 and 513 show the main connections for 30 MW turbo-alternators.

Stator Faults. The Merz-Price circulating current system is fitted to protect the alternator against faults between phases or between phase and earth. The system involves the use of six current transformers, three of which are placed in the phase leads from alternator, and three other similar transformers are placed in the star point connections which are connected to earth either directly or *viâ* a neutral earthing resistance. The secondaries of these transformers are connected in series with a relay across them.

During normal conditions the currents in the secondaries balance

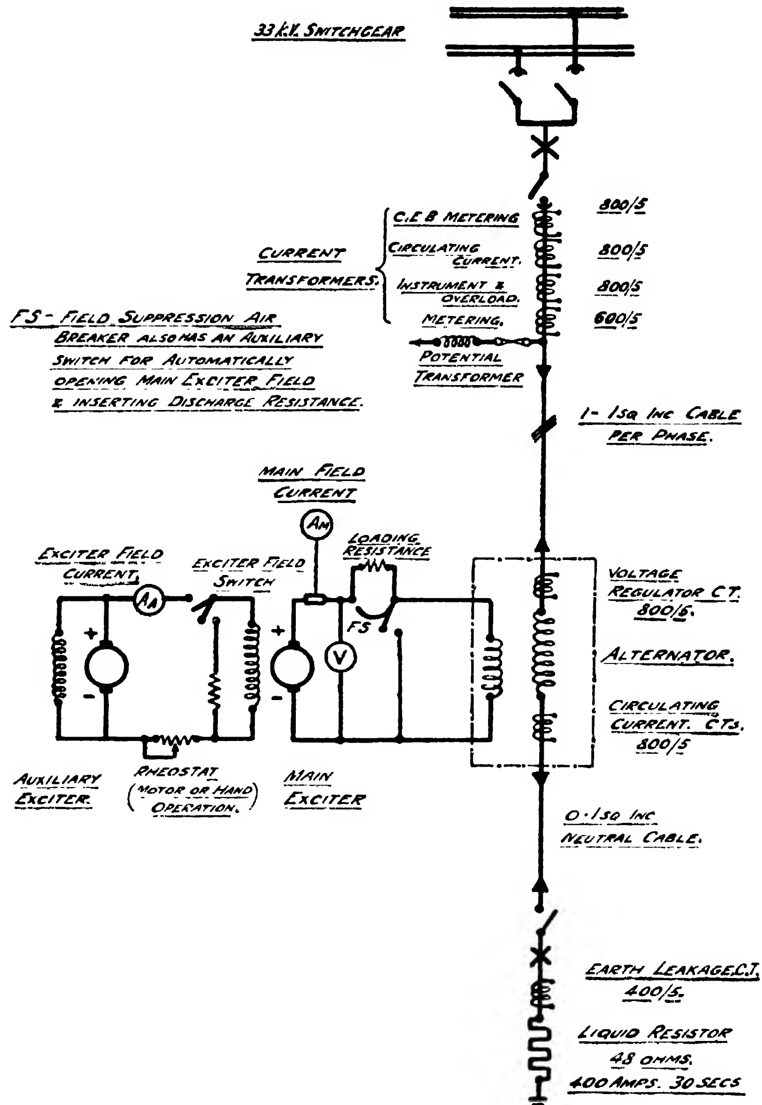


FIG. 512. Diagram of Main Connections for 30 MW 33 kV. Turbo-alternator.

and no current will flow through the relay circuit. When a fault occurs the currents no longer balance and the difference will flow through the relay coil. If this is sufficient the relay will operate,

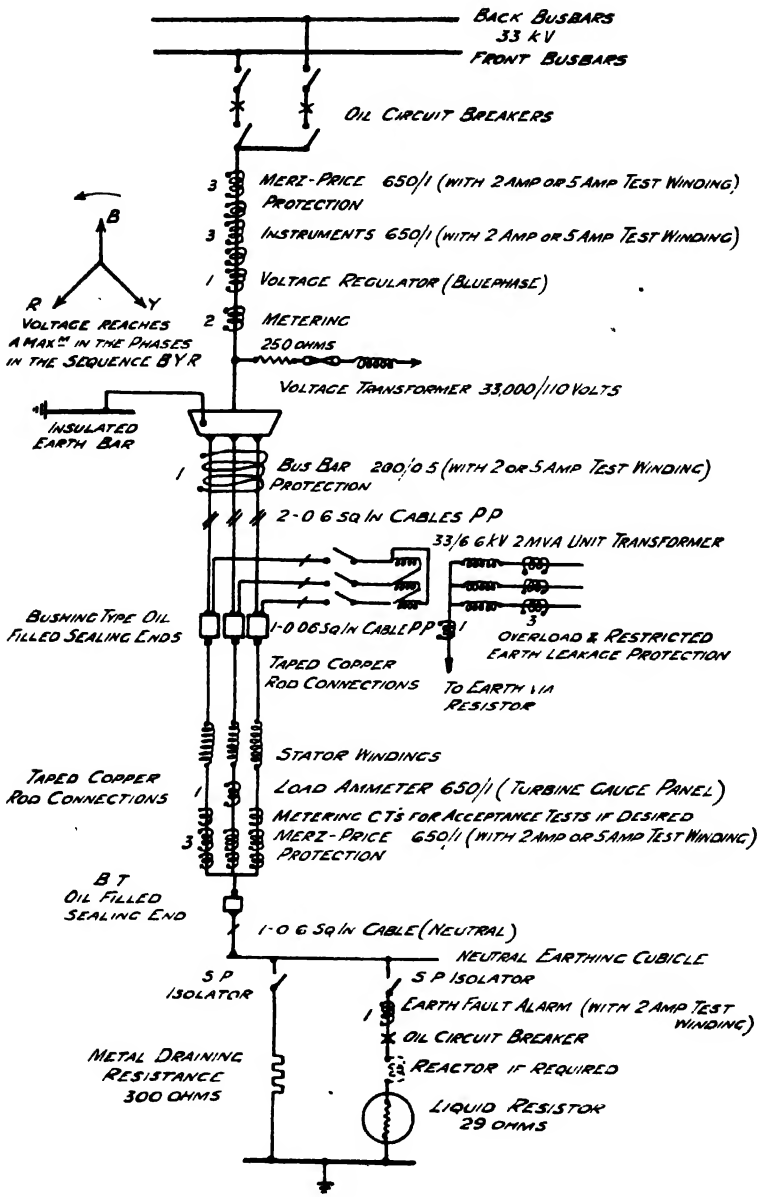


FIG. 513. Simplified Diagram of Connections for 30 MW, 33 kV Turbo-alternator with Unit Transformer.

thus closing the trip coil circuit and opening the corresponding circuit breaker, field suppression switch and probably the neutral circuit-breaker. The neutral earthing breaker associated with an alternator is usually tripped when a fault occurs on that alternator. Whether or not this breaker is tripped on such a fault, the opening of the alternator main breaker will result in the earth connection being disconnected from the sound system. If the neutral earthing breaker be non-automatic then with a fault on the corresponding alternator, the alternator itself will tend to feed the fault due to the residual magnetism until it slows down. On the other hand, if the neutral breaker is automatic the fault current circuit is broken and the arcing ceases. There may, however, be a " cock-up " of voltage on the alternator, but this is not transmitted to the system since the main circuit-breaker will be open.

Current transformers for such working should be specially balanced against each other and generally have distributed air gaps (D.A.G.); this is to avoid magnetic saturation of the transformers under heavy fault conditions and the possibility of operating the relay.

Compensating resistances may be necessary to equalise the loading of the transformers or if the mid-point of the pilot cable is in an inaccessible position. The ideal position for the point of connection for the relays is mid-way (equi-potential points) between the two sets of current transformers. It is seldom practicable to connect the relay at the equi-potential points due to the alternators being some considerable distance from the switchgear, where one set of current transformers are accommodated, as it would mean long pilots. This is overcome by inserting compensating resistances in the shorter length of pilot equivalent to the difference in resistance of pilots from where the relay is connected; this position being determined on site. The design of current transformers used will determine the necessity of such, as will be noted from the introductory remarks of this chapter.

Overcurrent protection may be provided by inserting fuses in the three pilot leads. They are chosen so that the fuses blow on the occurrence of a pre-determined overload, thus diverting the whole of the current from one set of transformers through the relay, and so causing it to operate. Kick fuses may also be inserted across the relay coils. Circulating current protective equipment with three current transformers in the circuit-breaker and three in the alternator neutral leads gives protection to the main phase cables in addition

to the stator windings. Each current transformer is balanced against any other five so that they can be grouped in any order.

If a fault to earth or a fault between phases occurs inside the protected zone the primary current will become unbalanced and consequently the current in the secondaries of the corresponding protective transformers will no longer be equal, and current will flow to operate the relay. If a fault to earth or between phases occurs outside the protected zone the primary current balance will always be maintained, therefore the stability of the protective system depends only on the balance characteristics of the current transformers. Cases are on record where through faults have been responsible for tripping Merz-Price relays. The most usual causes of such unwanted tripping are tapping the relays from a point on the circulating current pilots which does not correspond to the electrical mid-point or using current transformers of inadequate output for the pilot burden at the maximum value of primary current or using dissimilar current transformers in the star point and main circuit-breaker C.T. chamber. The cable lengths are usually reasonably short so that little trouble is experienced due to induced voltage in the sheaths. The pilot cable has an e.m.f. induced along its length by the proximity of the main cables when these are carrying in parallel large fault currents which return *viâ* ground to the source. Pilot cable breakdown may be caused both by current due to the induced voltage proper and by ground current traversing the sheaths. An open circuit in the pilot wires would also cause operation of the relay. Physical separation of power and pilot routes and the restriction of power network earthing to single points are employed to overcome such difficulties. The Self-balance and McColl protective systems are also employed for alternator protection. The McColl system gives much lower settings than that of the ordinary Merz-Price protection for they are of the order of 5 to 7 per cent. as compared with 15 to 20 per cent. full load current. The McColl system is essentially a Merz-Price system with biasing windings on the relays and in some cases settings as low as 2 per cent. are given. If the earthing resistance passes at least full load current (sometimes 60 per cent.) Merz-Price protection is quite satisfactory, but on the Continent where it may only pass 3 per cent. full load current then a very small relay setting is essential. In order to protect an adequate portion of the stator winding against earth faults with high resistance earthing it is necessary to have very low settings. To obtain these and at the same time

maintain stability on through-faults a biased relay must be used. Biased protection is more complicated and in any case Merz-Price biased protection can be given if desired.

Failure of Field and Field Suppression. Experience has shown that such failures are uncommon and protective equipment to guard against such a condition is unusual. If the field circuit of an alternator running in parallel with others is inadvertently opened the alternator will continue to run as an induction generator when (see also Rotor, Chapter XII) the speed will rise above synchronism to a point of balance between load and turbine governor characteristics. The output is at normal frequency since excitation is from the busbars, being obtained from the other alternators, and will help to some extent in supplying energy to the system. The excitation is wattless and its value probably in the region of 75 per cent. of the normal full load of the alternator. If the faulty alternator is not fully loaded and the other sets have greater excitation it is probable that it will remain in step and maintain almost its original output. The power factor will be low and leading as the stator will take the excitation from the busbars instead of the rotor and exciter. Much will depend on the system conditions obtaining at the time of the fault. If there is sufficient fully excited generating plant running to supply this excitation current, there will be little disturbance on the system. If, however, the running plant is insufficient to maintain the voltage at normal, some disturbance on the system is unavoidable whether the unexcited set is isolated or not. Normally no damage will be done to the faulty alternator even if it is allowed to remain on the system, and since, in this event, it does not greatly increase the liability to disturbance on the system, protective equipment is not essential. Under loss of field it would appear that it is possible to cause damage to the windings, rotating parts, and maybe the machine foundations. The alternator torque would tend to pulsate at slip frequency and be transmitted through the shaft.

Automatic field suppression equipment is included to prevent further damage to the alternator by suppressing the alternator field as soon as possible after an internal fault has been detected by the circulating current protective gear and the alternator disconnected from the system. Should the field suppression switch be inadvertently opened it is usual to arrange for the main circuit breaker to be automatically opened in such circumstances. The field suppression switch is arranged to be operated only from the circulating

current or the restricted earth leakage relay (the latter is sometimes used on small sets in place of circulating current protection) and not from the standby overcurrent protective relay. This is the

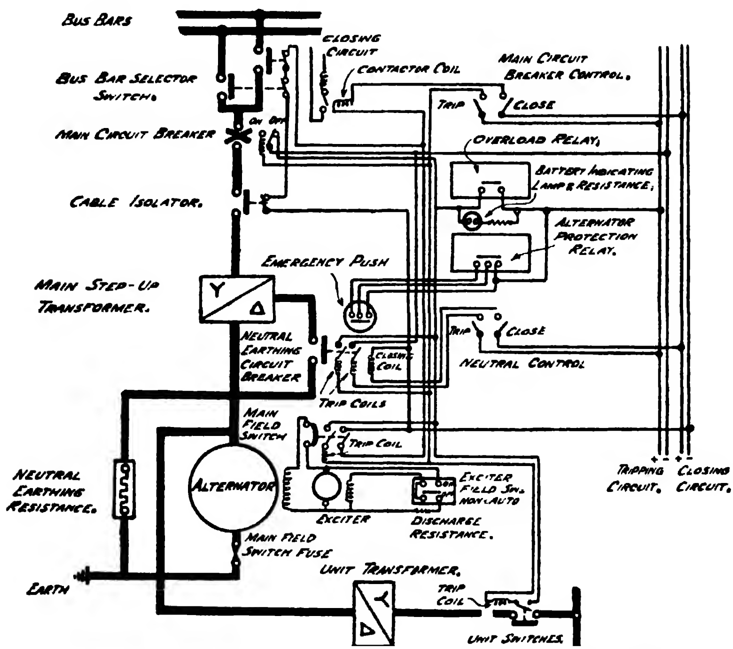


Fig. 514. Typical Diagram of Connections for Alternator and Transformer Switchgear.

Operations of Closing Circuit. The main field switch must be closed before the main circuit breaker can be closed unless both bus-bar selectors and the cable isolator are open. The neutral circuit breaker can be opened or closed independent of the other apparatus.

Operations of Tripping Circuit. Closing the main circuit breaker trip switch opens the main circuit breaker only. If the overcurrent relay operates or the alternator protection relay is operated by hand it trips the main circuit breaker only. If the A.P. relay operates on fault, the main C.B. trips first, then the main F.S. and neutral C.B. trip simultaneously also the unit transformer switch.

Operating emergency push is similar to above. If the main F.S. falls out accidentally, the main C.B. will not open. In some cases the main C.B. is arranged to open. *Exciter F.S. is non-automatic.*

best method as it is most rapid in action and is therefore the most satisfactory. The relays are fitted with double contacts, one for connection in series with the field switch trip coil, and the other with that of the main oil circuit-breaker. This enables the two tripping circuits to be kept separate and permits of individual control of

each device, either by hand operation using push-button switches or other relays, when their operation does not necessitate the opening of the rotor circuit, as well as the main circuit-breaker. In some installations an electrical interlock is included so that the main circuit-breaker cannot be closed until the field suppression switch is closed. There are various methods of suppressing an alternator field, and alternator manufacturers must always be consulted. Sometimes the turbo-alternator contractor supplies the field suppression equipment and at other times this is included under the switchgear and protective equipment contracts. The methods adopted on large sets are :—

(1) Automatic air breaker in alternator field circuit (open circuiting rotor field).

(2) Automatic air breaker acting as rotor slip-ring short-circuiting switch.

(3) Either of (1) or (2) with an auxiliary switch for inserting a discharge resistance across the main exciter field windings.

Tests made on alternators differ, but complete collapse of the magnetic field in 0·2 seconds is possible when the field is open-circuited. This results in an initial rise of up to 5 times normal voltage when the field switch is opened without any discharge resistance. If this is below normal flash testing voltage no danger need be incurred with modern sets. Times up to 15 seconds have been recorded for the collapse of magnetic fields to normal value. These tests are for a solid rotor core, the low maximum voltage being due to the damping in the solid metal. The peak voltage obtained with a given discharge resistance connected across the field circuit can be estimated as follows :

$$V_P = \frac{V(r + R)}{r}$$

where V is the applied voltage.

V_P is the peak voltage.

r is the field circuit resistance.

R is the discharge resistance.

This does not hold when a damping circuit is included and over-estimated voltages would obtain with large values of R, or when the field is opened by a switch without discharge resistance.

With a solid rotor the effect of the damping winding and the arcing at the switch is sufficient to limit the induced voltage to a maximum of from 4 to 6 times the initial voltage for a very short

period. With no damping winding the peak voltage may well be in excess of 20 times the initial voltage thus explaining the necessity for discharge resistances for D.C. machine fields or other windings having laminated magnetic circuits.

The opening of the main field circuit by a single or double switch without the use of a discharge resistance gives the most rapid discharge of the field, and therefore provides better protection. With solid rotor alternators it is quite safe and is to be preferred. Before applying it to rotors laminated or built up of plates it is advisable to ascertain that the inductive voltage-rise, when the field circuit is broken, is within the value of the rotor insulation breakdown test voltage. This can be done by connecting a needle spark-gap set for a given value across the slip-rings. If no discharge occurs at the gap the discharge resistance may be safely omitted. A discharge across the needles indicates that there is not enough damping effect in the rotor and a discharge resistance is essential. The elimination of the discharge resistance improves the efficiency of the protective equipment in addition to reducing the cost by using a standard air breaker without resistances. The air breaker is not fitted with blow-out devices as it is not desirable to rupture the arc rapidly when the breaker is opened. The arc acts as a self-regulating resistance in series with the rotor field windings and prevents the inductive rise in the rotor voltage from becoming unduly high. This is much more effective than the use of ordinary resistances since the latter can only be inserted in large steps, whereas the arc gives a smooth and rapid change from a negligible resistance (when the breaker just starts to open) to an "infinite" resistance when the arc finally disappears. A slip-ring short-circuiting switch is preferred by some makers, although the discharge time is about twice that obtained with the first method. As the main exciter armature is short-circuited it is necessary to insert a "loading" resistance in the armature circuit to prevent sparking at the commutator. The usual arrangement consists of a single-pole, double-throw switch in the rotor circuit. In the normal position of the switch the exciter is connected directly to the slip-rings, the "loading" resistance being short-circuited. On opening, the slip-rings are automatically shorted and the resistance connected in series with the exciter armature. With modern sets there is no necessity to ensure a definite sequence in the order of opening the main circuit-breaker and field air-breaker. The essential feature is that the rotor field is broken as rapidly as possible when a fault

develops. The field suppression switch also provides protection to the rotor field windings.

Failure of Prime-mover. Automatic protective equipment is not included for this purpose although the reverse power relay has been employed. The disadvantage of this relay is that false operation may take place, for reversal of current in an alternator equipment does not necessarily imply faulty windings.

Reversal of power in healthy alternators is often brought about by system disturbances due to synchronous plant "pumping" back and power will sometimes circulate momentarily between two or more alternators if there is any tendency for the sets to drop out of synchronism on heavy faults before the governors can fully respond. Thus it is possible for a healthy alternator to be tripped off the bars under such conditions unless the reverse power relay is given a high setting, or alternatively has a delayed operation.

Probably the most satisfactory method is to provide an emergency hand tripping-device on the turbine gauge panel. This device can be arranged to trip the main circuit-breaker and the emergency trip gear on the turbine. The set would motor in synchronism, and if the trouble is likely to be prolonged it should be taken off the bars. The alternator power factor meter and ammeter in the control room will indicate a change in operating conditions, and failure of prime mover will result in alternator running as a synchronous motor at a higher or leading power. An indicating wattmeter will read in opposite direction and sometimes a small portion of reverse scale is included on the meter scale. If there is a possibility of restoration of steam supply immediately and gradually, the set may be put back into commission without any undue disturbance.

Faulty Synchronising. Mistakes on the part of operating engineers when synchronising an alternator may result in interruptions to supply and there are a number of schemes embodying relays. It may be mentioned that many large stations still rely entirely on the operating engineer for such duties. Two relay schemes are :—

(1) Synchronising relays which prevent the closing of the main circuit-breaker until the incoming set is in exact synchronism with the running plant.

(2) Instantaneous overcurrent relays, which are effective during the synchronising operation only to re-open the main circuit-breaker of the incoming set in the event of the closing operation being incorrectly timed.

The first method is for use where the main circuit-breakers are electrically operated and has the advantage that the windings are

not subjected to the stress consequent upon switching the set on to a system from which it differs in phase. The Metropolitan-Vickers' synchronising relay is simple, accurate, robust, and operates to

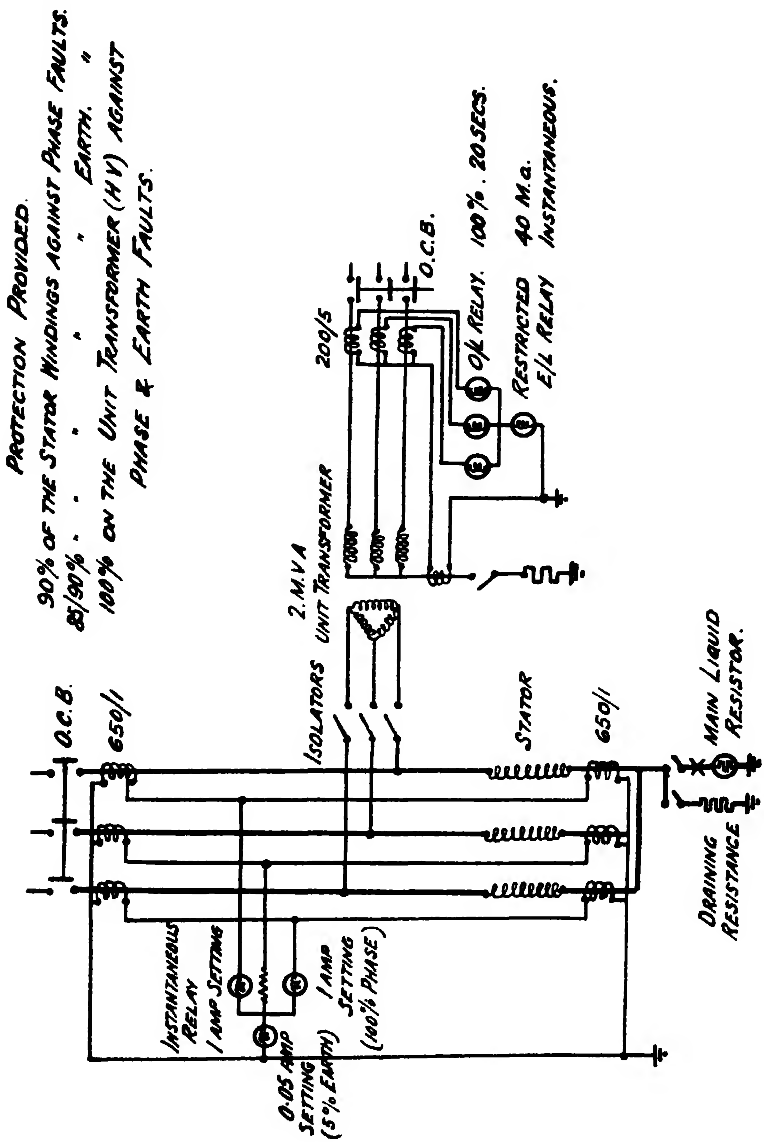


FIG. 515. Protection for 30 MW, 33 kV Turbo-alternator with Unit Transformer.

interrupt the circuit of the main oil-breaker closing coil, until the set is in synchronism. The operating engineer is relieved of all responsibility for correct synchronising, since it is impossible for him to close the main breaker except under the correct synchronising condition.

The second method does not prevent incorrect timing of the closing of the main breaker, but if this should happen the breaker is immediately re-opened before any serious disturbance takes place on the system. The setting of the overcurrent relay can be made low, usually about 25 per cent. of the normal full load of the set being recommended. The magnitude of the current which will flow into the set in the event of a " bad shot " at synchronising will often be considerable, making operation of the relay certain and definite. When the synchronising operation is completed the relay is made ineffective for further tripping by opening a switch connected in series with the tripping contacts.

Fire Risks. The risk of damage by fire in alternators is more pronounced when they are of the enclosed type, for if an arc occurs it is quickly fanned into flame by the draught in the ventilating ducts. In such cases it is essential that the faulty alternator be instantly disconnected from the bars and the rotor field removed at the same time. In some installations the emergency stop valve is closed on the operation of the Merz-Price Relay, Unit Transformer (L.V. side) Earth Leakage Relay, Bus-Zone Protective Relay and Emergency Push Button Switch, all of which are connected in parallel to the master tripping relay. A further means of minimising damage by fire is to use a " closed-air-circuit " ventilating system as outlined in Chapter XII. The supply of oxygen in such a system is limited and a fire-extinguishing apparatus may be included.

External Faults. The simplest method of preventing internal damage to an alternator due to the persistence of excess current under external fault conditions is to include stand-by time-delay protection. Although overcurrent protection will safeguard an alternator, it is insensitive, and the fault current must be well above normal load before the protection is afforded. Some engineers prefer to rely on the Merz-Price protection only and have omitted stand-by overcurrent since it is considered necessary to keep the alternator on the busbars under all conditions excepting an internal fault. This seems a reasonable assumption, for the actual output will of course be limited by the turbine.

The most serious external fault is that giving rise to unbalanced

phase current, usually caused by faults to earth or between phases on feeders and bus-bars which are not cleared correctly by local protective equipment. This condition corresponds to the super-

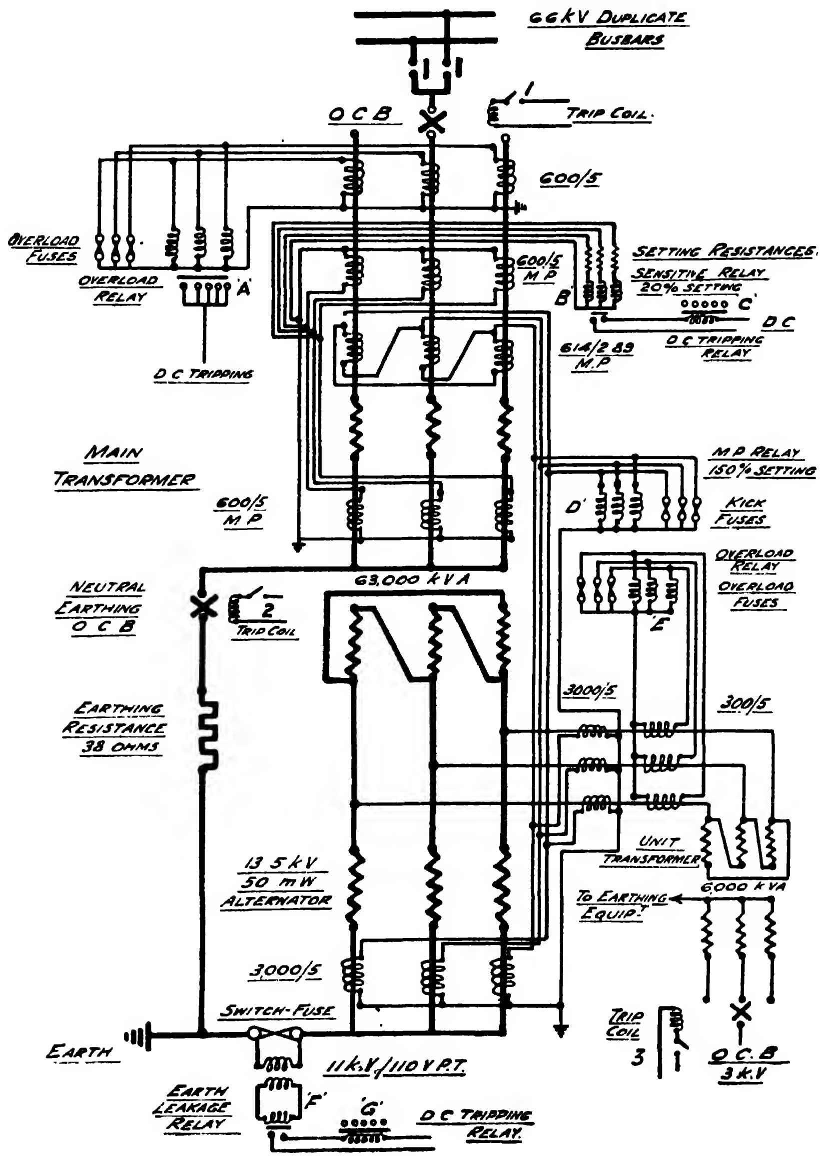


FIG. 516. Combined Alternator and Transformer Protection.

imposing of single-phase loads upon a balanced three-phase load condition which, if maintained, is dangerous as it superimposes a single-phase alternating field upon the rotating field of the alternator stator, thereby inducing current in the rotor and so setting up local heating. Cases are on record in which the effect of heavy unbalanced currents maintained for a comparatively short time was sufficient to raise the temperature of part of the rotor wedges to such a value that they became plastic, were extruded from the slots and damaged the stator core. Adequate protection against single-phase load is not given by the more usual forms of stand-by over-current protective gear, as it is necessary to set the relays so that they will not operate under normal full-load conditions. A single phase-to-phase fault or an unbalanced loading of about 50 per cent. of normal full load on an alternator may give rise to dangerous heating of the rotor. To guard against such conditions it may be necessary to include protective apparatus that is sensitive to unbalanced or single-phase loading conditions much below normal full load, yet remain unaffected by ordinary balanced load. To fulfil these conditions the B.T.H. Co. have developed a phase-unbalance protective system that responds to what are termed " negative and zero phase sequence components " of three-phase currents. The design of some alternators is such that single-phase running would not have any detrimental effect on the rotors and before deciding on the protective system the alternator manufacturer should be consulted.

When the alternator is connected direct to a step-up transformer a single-phase load may not have ill-effects to the same extent in heating the rotor as single-phase running on the set itself.

Alternator-Transformer Protection. When alternators are connected directly to step-up transformers they have to be protected as a unit for there are no means of automatically isolating one from the other. The application of circulating protection to alternator-transformer equipment suffers from the disadvantage of poor sensitivity for high-voltage earth faults. Protection for phase faults on either the alternator or transformer may be obtained by means of a normal circulating current system arranged for overall protection and operating on a common high-voltage and low-voltage phase fault relay. The protection for earth faults on the high voltage and low voltage system is separated and operates through two independent earth leakage relays. The low-voltage earth fault relay operates from a current transformer placed in the

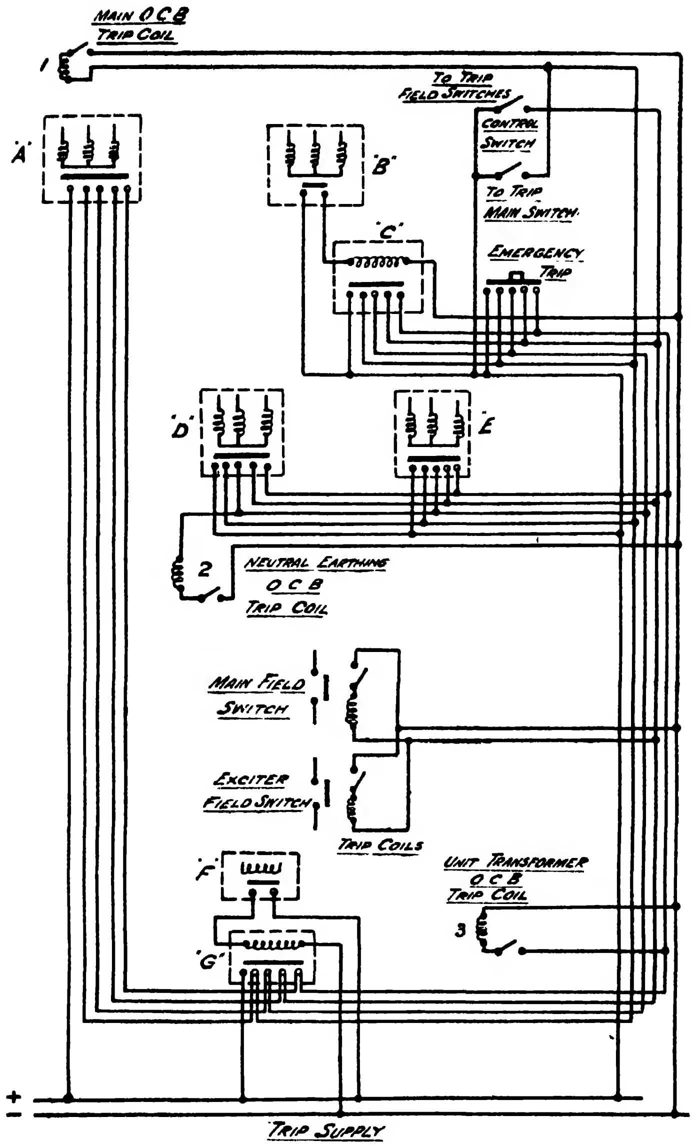


FIG. 517. Diagram of Tripping Circuits for Fig. 516.

alternator neutral while the high-voltage earth fault relay operates on the restricted earth leakage principle from additional windings on the high-voltage line current transformers used for phase fault

protection and also from an additional transformer mounted in the power transformer neutral connections. The alternator winding and the primary windings (LV) of the step-up transformer form a separate system, and the star point of the alternator windings which is the neutral point of this system is earthed through a voltage transformer the primary terminals of which are short-circuited by a high-rupturing capacity fuse. An alternative is to short-circuit the secondary terminals of this voltage transformer and has the advantage that the current to be interrupted is smaller. A fault on the LV terminals of the main transformer has been known to be of such severity as to do considerable damage to the earthing fuse when the first method is employed. In the event of an earth fault on this system resulting in the fuse being blown, the voltage transformer is energised and its secondary winding operates an earth-leakage alarm. The earth-current due to the fault is restricted to the small current which the impedance of the voltage transformer would permit to pass. Should a second earth fault occur this would constitute a fault between phases, and the Merz-Price circulating current protective gear would operate. The operation of either the circulating current or the restricted earth leakage relay indicating an internal fault in the alternator, unit transformer, or associated cabling would trip the main circuit-breaker, field suppression breaker, main transformer neutral circuit-breaker and the unit transformer LV circuit-breaker. The unrestricted earth leakage relay which would only be operative by an external fault, is arranged to trip only the main circuit-breaker. Figs. 514 to 516 show typical protective systems for combined alternator-transformer protection. Fig. 517 indicates the tripping circuits for Fig. 516 and the cabling required is shown in Fig. 518.

Transformer Protection. The circulating current system may be used for transformers with the exception that kick fuses are inserted across the relay coils. These prevent the relay operating at the instant of switching in the transformer when the current rush is above the normal and a certain amount of out-of-balance exists. Most of the current is diverted from the relay coil which does not operate until after the fuse has blown. The sensitivity of the combination is thus determined by the fusing current and not by the setting of the relay which must be set to operate at a current value less than the fusing current of the wire. Similar fuses are required when overcurrent and earth leakage systems are adopted. The current transformers used must have

ratios varying in proportion to the ratio of the power transformer. With a star-delta transformer the current transformers on the star

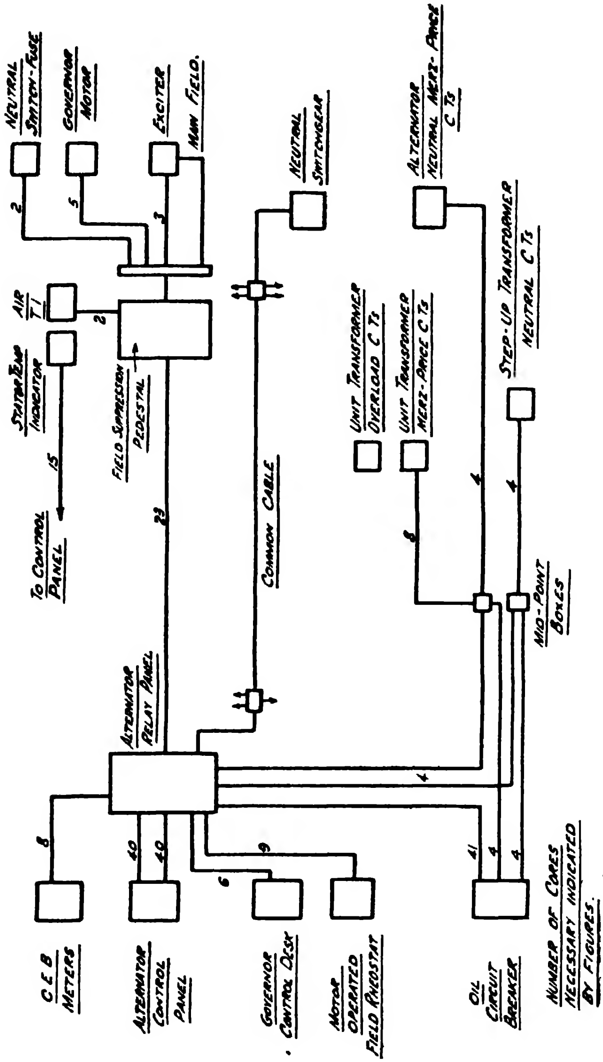


FIG. 518. Multicore Cabling for Alternator and Transformer Equipments.

side are connected in delta while those on the delta side are connected in star. To obtain balance it is necessary that the secondary current of the transformers connected in star should be $\sqrt{3}$ times the secondary current of those connected in delta. On-load tap

changing affects the balance of circulating current protection due to changing of transformation ratio. For transformers having on-load tap changing and a fairly wide transformation ratio, balanced current can only be used if relatively coarse settings are permissible. Restricted earth leakage protection is a suitable alternative and back-up overcurrent protection can also be used. When transformers are operating in parallel it is necessary to have inter-tripping between the circuit-breakers on either side of the transformers. The works and auxiliary transformers are usually covered by combined overcurrent and earth leakage protection, the current transformers being accommodated in the circuit-breaker units.

Another form of transformer protection, known as the Buchholz relay, has been used, particularly on large transformers. This relay is a simple float device placed in the connecting pipe between the main tank and the conservator, and is applicable to transformers fitted with conservators. Normally the closed sight chamber is full of oil and at the top of the chamber is a float. In the event of any gas being given off by the transformer the bubbles rise into the sight chamber, displacing the oil so that the float drops, making contact across an alarm circuit. When such a protective device is first installed it is usual to connect for alarm operation only to prevent inadvertent operation due to air being trapped in the transformer tank when the relay is installed. It is also possible for such a relay to operate if there is a sudden abnormal drop in atmospheric temperature, particularly if this coincides with low-load on the transformer, resulting in considerable drop in oil level. In the event of oil leakage from the transformer tank the relay will operate well before a reduction of the oil can have serious consequences. Discrimination between operation due to oil leakage and operation on electrical faults in the transformer can be made by inspection of the conservator oil level. Fig. 519 shows the protective equipment for a star/star station transformer. On one station where 132/3·3 kV star/star station transformers are used they have resistance earth fault and overcurrent protection on the H.V. side and have tertiary windings with overcurrent protection. The H.V. star point is solidly earthed. On the L.V. side, overcurrent is provided and the L.V. star point is earthed through a voltage transformer, the secondary of which is connected to a relay and operates an alarm in the control room. Should an L.V. earth fault occur, intertripping is provided from the H.V. to L.V. sides and automatic

closing of the station board bus-section breaker is included should either the station transformers trip on a H.V. fault.

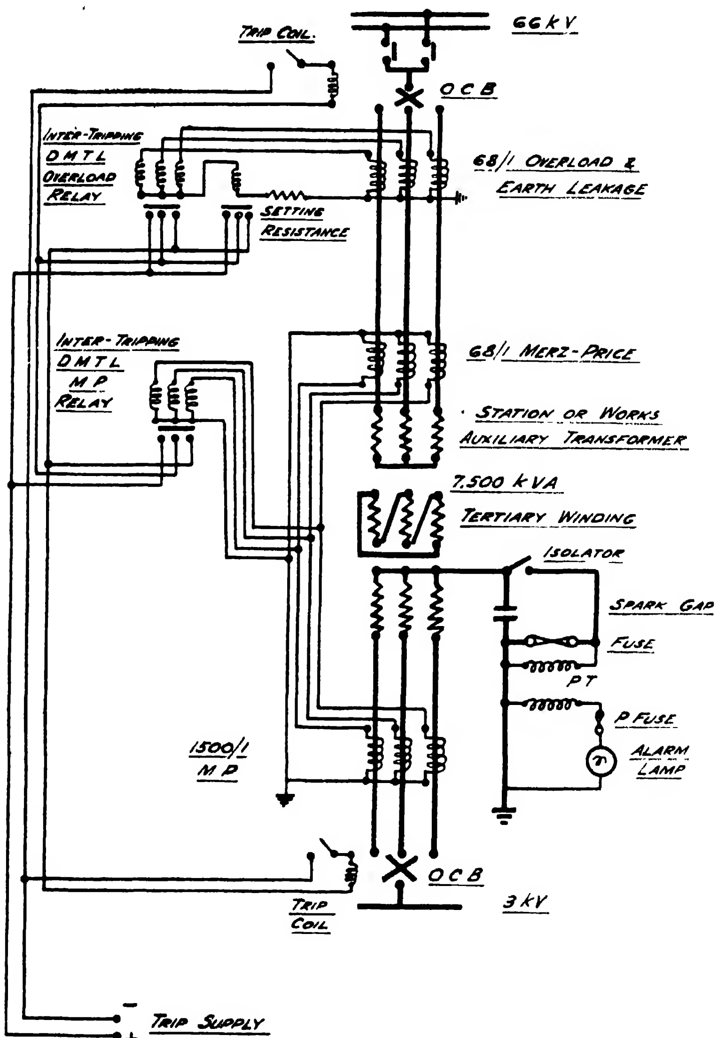


FIG. 519. Station Transformer Protection.

Reactor Protection. Combined overcurrent and earth leakage protection may be used, but much will depend on the switchgear arrangements. In some cases the reactors are protected by

restricted and unrestricted earth leakage relays and the operation of either would trip both reactor circuit-breakers. The restricted earth leakage relay, being discriminative, is given a minimum time setting and the unrestricted relay is time-graded.

Cable Protection. The cables are covered by the protection for the individual items of plant with which they are associated. They are in the protected zone and further protection is unnecessary.

Motor Protection. The protective devices for motors should be simple and robust as the majority of the services are such that the motors cannot be overloaded. Further, it is undesirable to trip them out for anything other than a fault which if not interrupted would cause dislocation of a large portion of the auxiliary system.

The services where overloading is most likely to occur are the coal and ash-handling plant auxiliaries such as conveyors, elevators, hoists, etc., but as these are usually slip-ring motor drives with rotor starters the required degree of overcurrent protection is easily obtained. No-volt protection is required on the individual motor drives for these services so that in the event of failure of supply the stator switch and rotor starter are both opened. Speaking generally, no-volt protection should not be fitted on important auxiliary circuits since a momentary fall in voltage, sufficient to operate these trips, may be due to an external fault. Where such trips are included time delays may be fitted. It appears better to omit no-volt coils from important auxiliaries and rely on the overcurrent protection to trip the motors if the voltage should fall owing to the increased current taken from the line.

No-volt features are of course always to be found on D.C. auxiliaries. An advantage claimed for these trips on non-essential auxiliaries is that it clears the system as far as possible when general trouble occurs. The practice nowadays is to switch motors "direct on line" and dispense with no-volt protection. Should the voltage drop to a dangerous value then the switch will be tripped by over-current due to the considerable increase in current taken by the motor. The motors are usually guaranteed to keep running with a sudden voltage drop to 66 per cent. of normal voltage. Care should be taken when carrying out voltage adjustment on alternators, particularly where interconnection to other sections of the system is by means of interbusbar transformers. Cases are on record where extreme adjustment of exciter field rheostats has been carried out without altering the taps on the interbus transformers which resulted in the flow of a large wattless current from different sections of the

switchboard and caused tripping of the overcurrent relays on the interconnectors. In such cases the alternators are under-excited and the terminal voltage is reduced and if load is shed the speed rises immediately thereby increasing the frequency. Under such conditions the motors driving the various auxiliaries are overloaded and may trip out.

Adequate torque margin to start and accelerate feed pumps for very large unit installations necessitates an auxiliary supply affording not less than some 80 per cent. of normal voltage during starting.

The use of overcurrent coils with single time lag trips is quite suitable for motors of 500 B.H.P. In some cases double and triple time lag trips are fitted to allow for the necessary high-starting currents of the motors and provide overcurrent protection during normal running conditions.

There are two extremes in setting overcurrent coils and time lags. One is with the overcurrent coil set high and the time lag short, and the other is with the overcurrent coil set low and the time lag long. Important auxiliaries should not be allowed to trip on the occurrence of small overcurrent, but heavy overcurrents (a rare occurrence) have to be provided for. One method of protection is to have two of the overcurrent trips set high (250 per cent. F.L. current) and the third trip at 125 per cent. full load. The third trip does not operate the circuit-breaker but only closes an alarm circuit and so warns the operating staff.

The smaller motors up to, say, 70 B.H.P. usually have high-rupturing capacity fuses as back-up protection, the individual motors being controlled by "direct on line" starters or stator switches fitted with overcurrent time-lag trips of the dashpot or thermal types.

When planning a distribution system for auxiliary supplies it is advisable to obtain from the plant contractors a complete schedule of starting currents and the duration of the starting peaks so that the fuses will be designed to blow at a margin above the starting currents of the respective motors. The fuses are therefore more in the nature of fault-protection and can be obtained for service up to 35 MVA at 600 volts. Assuming the starting current of a squirrel cage motor to be 100 per cent., then double cage and triple cage motors would be 70 per cent. and 50 per cent. respectively. In the case of a 90 B.H.P. ventilating fan motor with an impeller weight of 390 lb. and radius of gyration $17\frac{1}{2}$ in., the motor would run up to speed in about 15 to 20 seconds. In practice the running-up times are found to vary over wide limits.

Some idea of the duration of the starting currents will be obtained from the following :—

30	B.H.P.	extraction pump	8–10 seconds.
8/25	,,	barring gear	4–12 ,,
8	,,	high pressure oil pump	2–12 ,,
2½	,,	auxiliary oil pump	2–8 ,,
200	,,	circulating water pump	4–10 ,,
120	,,	alternator vent fan	6–10 ,,
250	,,	boiler feed pump	5–10 ,,

The starter overcurrent trips should be set to give the necessary delay required for the starting peak, but in some cases the time delay will be much coarser than that desired for normal overcurrent setting. The action of these overcurrent time-lag trips will be instantaneous under fault conditions unless a special relay, having inverse time characteristics, is fitted to give the desired discrimination. This is sometimes employed where the individual starters are rated on the motor output and not on MVA available under fault conditions. If single-phase loading conditions are possible a negative phase sequence relay could be fitted which would also operate under faults between phases.

Switchgear Protection. The protection of switchgear has received much attention in recent times, probably due to the failures which have occasionally occurred and the very large units now being installed. The protection is required to cover those sections of the circuit-breaker not protected by the circuit protective equipment. These sections include the bus-bars, isolating devices, circuit-breakers and the connections between them, the whole being termed the bus-bar zone. "Leakage to frame" protection, which is essentially a particular form of zone protection has been applied to both individual switch and transformer units for many years.

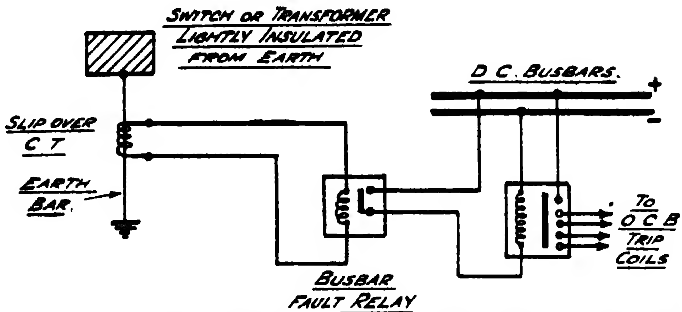
A fault in the bus-zone is fed from all sources of power connected to the bus-bars, so the first requirement is that these sources should be immediately disconnected. Some degree of bus-bar protection is afforded by overcurrent protection on the circuits feeding into the fault, but this is very coarse.

On referring to Regulation 8 of the Electricity Regulations under the Factories Acts it would appear that the inclusion of bus-bar protective equipment is desirable if not essential.

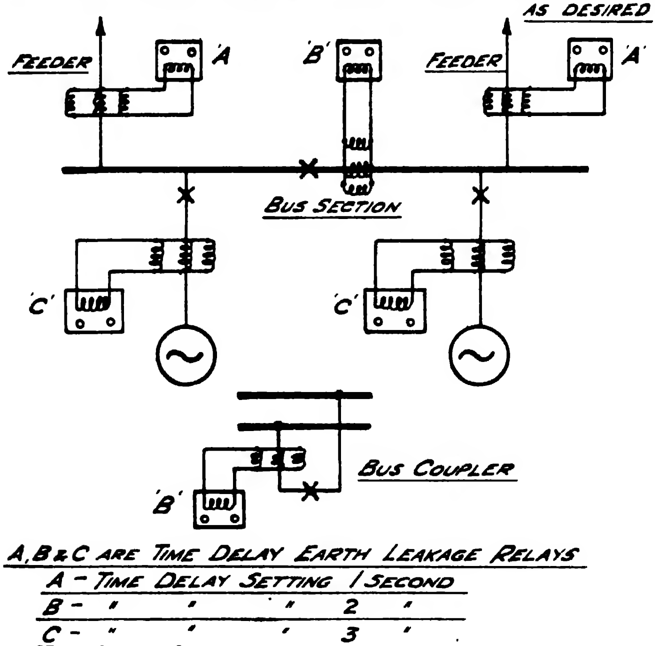
This regulation states :—

" Efficient means, suitably located, shall be provided for protect-

ing from excess current every part of a system, as may be necessary to prevent danger."



(a) FRAME LEAKAGE RELAY ARRANGED TO TRIP CIRCUIT BREAKERS AS DESIRED



(b) LAYOUT OF TIME DELAY EARTH LEAKAGE RELAYS

FIG. 520. Bus-bar Protective Systems.

Bus-bar protective systems are designed so that on the occurrence of a fault or accidental contact by men working on bus-bar spouts, etc., in the bus-bar zone of a switchboard special relays auto-

matically open all circuit-breakers through which power can be fed into the fault. The system of protection should be such that any leakage of current from the busbars on each section would cause all incoming supplies to the section or sections involved to be disconnected. This arrangement may include the summation method utilising a core balance transformer surrounding each three-phase cable and connected to a relay and auxiliary equipment.

In the event of a through fault the current entering and leaving the busbars will summate to zero so that the relays will remain inoperative. When an earth fault occurs within the protected zone the core balance current transformer will have an out of balance current set up which in turn will operate the tripping relays. Provision should be made to prevent inadvertent operation through accidental tripping of any relay for complete reliability in this respect is essential. There are numerous systems of protection available.

The three chief systems in use at the present time are :—

(1) Circulating current or differential protection similar to that used for alternator and transformer protection.

(2) Leakage to frame protection.

(3) Time delay earth leakage relays.

Leakage to frame protection is especially applicable to metal-clad switchgear in which the bus-bar phases are in separate chambers, as this form of protection can only deal with earth faults. It can be adapted to cellular gear, the individual equipments being connected to the earth bar instead of the structure, which, if of stonework, is already of a semi-insulating nature.

The whole of the metal sheathing of the cables and the structural steelwork are lightly insulated from any earthed metal and from the lead sheaths of the incoming and outgoing cables. The frame is bonded to an earthing bar and connected to earth by a conductor which is the primary of a current transformer.

If a breakdown of the insulation in the bus zone of the equipment takes place a current will flow in the conductor which connects the earthing bar to earth. The current transformer is connected to a relay and when this becomes operative energises a multi-way tripping relay which closes the trip circuits of all the circuit-breakers of the associated switchboard or section thereof. Operation of the earth fault relay thus causes complete shut down of perhaps a large portion of the station capacity. The disadvantages of this system

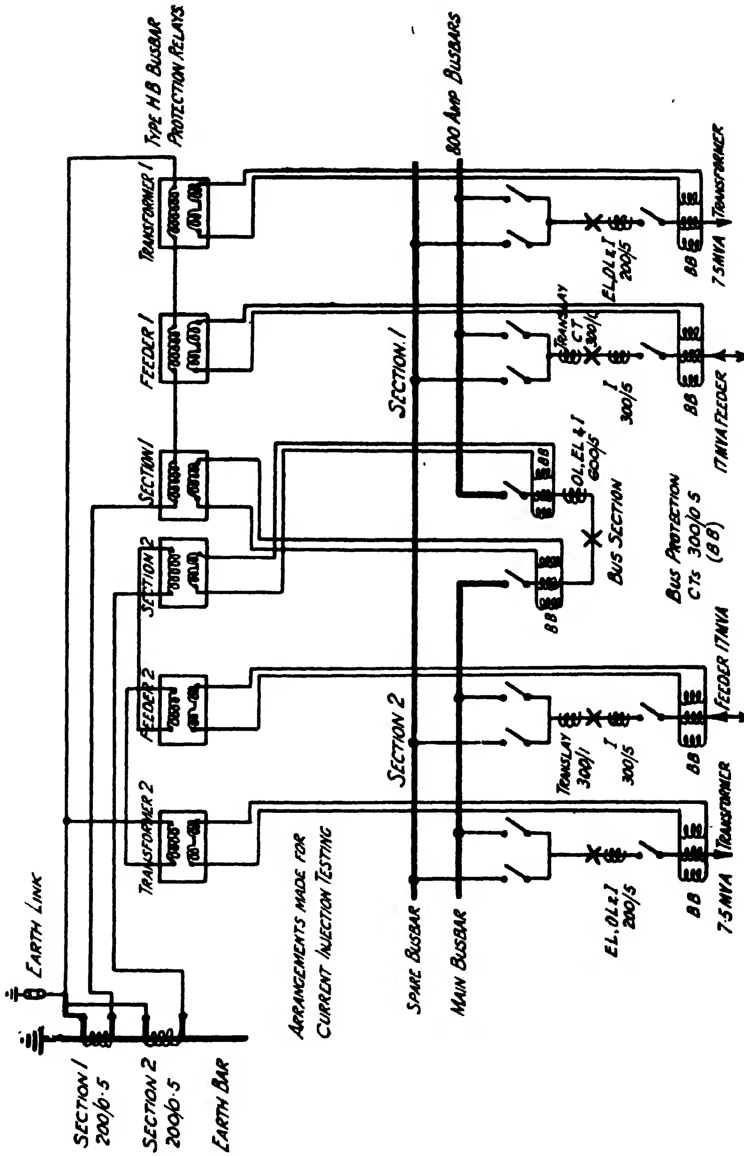


FIG. 521. Bus Zone Protection for 33 kV. Switchgear.

are that a large portion of the supply depends on the stability of one relay, and inadvertent operation of this relay, either electrically or by vibration, will be serious.

The possibility of parasitic currents flowing in the earth conductor and the danger of making temporary earths thus short-circuiting the protective system have also to be borne in mind. In this system it is desirable that the source of D.C. supply for the various control and indicating circuits should not be earthed.

Care is required in the installation of the main cables and these should be placed central in the current transformer, for the out-of-

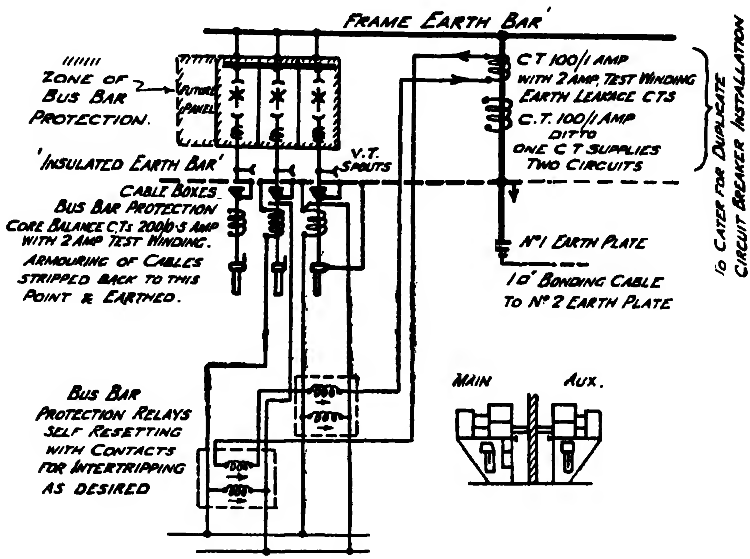


FIG. 522. "Translay" Earth Leakage Bus-bar Protection.

balance current should be low enough to be certain of satisfactory protective balance between current transformers. Simplified diagrams are shown in Figs. 520 to 522.

Neutral Earthing. The chief advantages of neutral earthing are :—

(1) Persistent "arcing grounds" are eliminated.
(2) The use of sensitive protective apparatus is possible.
(3) High-voltage shocks to the system and apparatus are reduced.

The high-voltage neutral is earthed mainly for the protection of the system while the low-voltage neutral is earthed chiefly in

order to reduce the possible danger to human life. Both systems may be either earthed direct or through an earthing resistor.

Where energy is transformed suitable provision should be made to protect the lower voltage system from becoming charged above its normal voltage by leakage or electrostatic induction (capacitance effect) from the higher voltage system.

The use of spark gaps and direct earthing are the usual methods for the lower voltage systems in power stations. Fuses may also be inserted in the medium voltage neutrals and these allow a system to operate with an earth fault on one phase until it is convenient

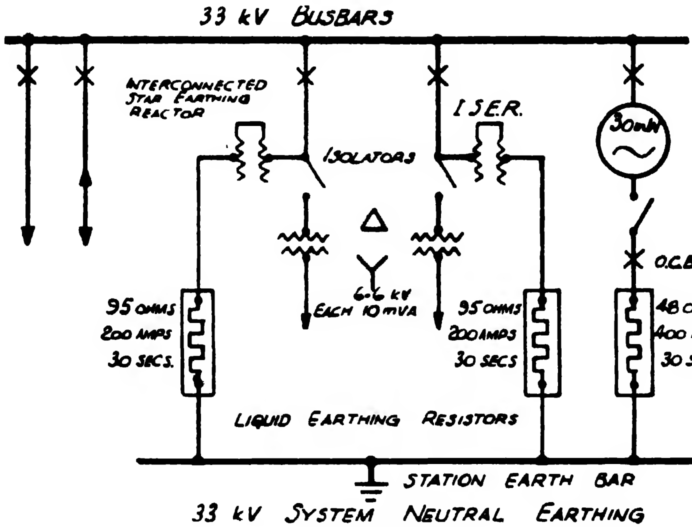
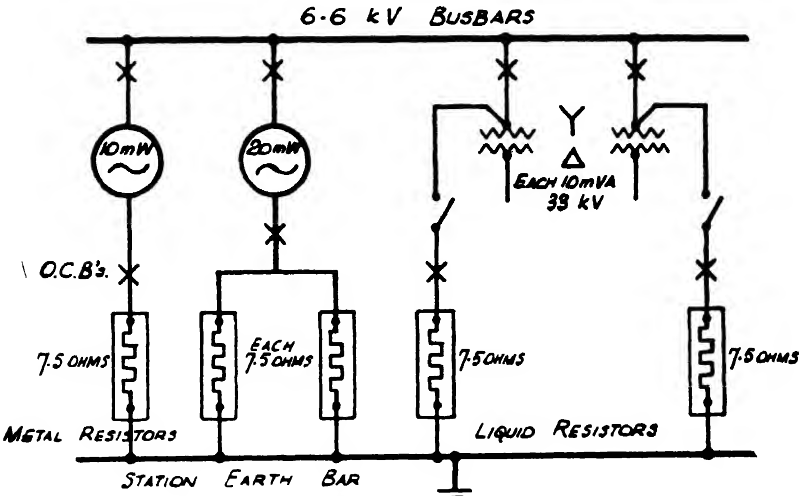


Fig. 523.

to clear same. If a neutral point is not available at all times, as for example where the station is required to be shut down at certain periods, the use of a special earthing transformer is resorted to.

Where alternators are connected direct to the bus-bars the practice is to select the neutral point of the largest set and earth this only *viâ* an earthing resistance. Where one earthing resistance only is provided as in smaller stations the efficiency of the earthed neutral is higher when the smallest machine has its neutral earthed and the others left isolated. A much larger system can, in general, be protected by a given resistance when the smallest machine is earthed on account of the increase in the lagging component of the fault current. If the alternators be connected solidly to step-up trans-

formers it is usual to connect each alternator neutral through a fuse or voltage transformer. As each unit constitutes a separate system all neutral points may be earthed together. Care is required in the handling of neutral earthing conductors for they are often thought to be at earth potential but not solidly earthed. Accidents have occurred from voltages probably obtaining due to out of balance or harmonics in the system. The high-voltage system earthing point is taken from the step-up transformers, only one neutral being earthed through a resistance at a time. The object of earthing only



6·6 kV SYSTEM NEUTRAL EARTHING.
FIG. 524.

one alternator neutral point at a time with sets connected direct to the bus-bars are :—

(1) To keep the resistance between the neutral point of the system and earth constant, otherwise the leakage current may vary considerably.

(2) To avoid interchange of triple-frequency currents between sets. In the event of ill-timed synchronising it prevents a cross-current circulating between sets.

(3) It eliminates multiplicity of earthing resistances.

This method of connection, however, results in the earth fault causing a rise in potential on the neutral bus-bar.

Where cables and conductors carrying currents containing harmonics and laid parallel to communication circuits, particularly telephones, the electromagnetic field set up by them will induce

e.m.f.'s of a corresponding frequency in the communication circuits and cause considerable interference.

There is no fixed rule for determining the ohmic rating of the neutral resistor, the two most important features to be considered are the type of protective gear used and the amount of alternator windings to be protected against earth faults. The function of the neutral resistor is to limit the current on the occasion of a fault and so protect the plant and switchboard from abnormal current

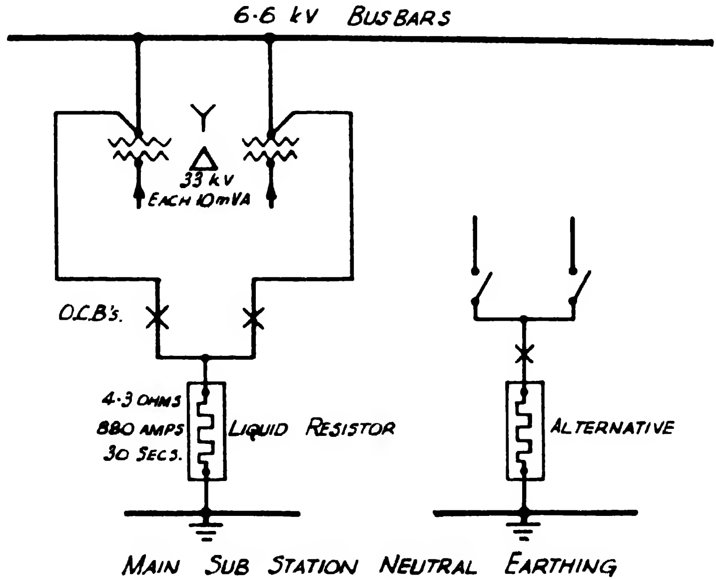


FIG. 525.

stress. On the other hand a reasonably large fault current enables the alternator windings (or transformer) to be more adequately protected; the voltage and transient voltage stress on the system to be reduced; the margin of safety in fault current over the fault setting of the protective systems to be increased, and the fault to be easily located.

A 52 MW, 11·8 kV set is connected to earth through a voltage transformer primary winding, which has a non-linear resistance connected in parallel. The set operates with a step-up transformer.

In a similar case of a 50 MW, 13·2 kV set the neutral point of the alternator is connected to earth by way of a single phase 50 kVA, 13·2 kV/220 V. transformer. An 0·63 ohm resistor and an alarm

relay are both connected across the terminals of the secondary winding of this transformer.

With 33 kV. turbo-alternators it has been recommended that the neutral points be earthed permanently while connected to the busbars to prevent high surge voltages on the star point of the windings. If the alternators are of similar design they can be connected through isolators to a common earthing bar connected to earth through a drainage resistance of about 200 ohms. 33 kV. turbo-alternators have been operated without any such resistance, running with insulated neutrals after having been synchronised. If it is necessary to take the station earth (29 ohms on 33 kV. system for 30 MW full load) from the alternator a triple harmonic current will flow from the star point to earth through this resistor. The triple harmonic current is due to the triple harmonic in the phase voltage and the large capacitance of the 33 kV. system. Alternators are designed to have an almost perfect sinusoidal wave shape but a small triple harmonic is unavoidable, and due to the capacitance of 33 kV. systems the triple harmonic current cannot be ignored. Similar conditions obtain on lower voltage alternators and must be considered when arranging earthing systems.

The method of estimating the protected portion of the windings is now given.

Let V = Phase voltage $= \dfrac{E}{\sqrt{3}}$ where E is the line voltage.

I = Normal load current of alternator.

i = Primary out-of-balance current.

a = Relay setting.

$= \dfrac{100i}{I}$ per cent.

I_e = Maximum earth current.

R = Ohmic value of resistance.

$$\text{Percentage of winding unprotected} = \frac{100 i R}{V}$$

$$\text{but } R = \frac{V}{I_e}.\ \text{and } i = aI.$$

$$\therefore \text{ Percentage of winding unprotected} = \frac{100\,aI}{I_e}$$

$$\therefore \text{ Percentage of winding protected} = 100\left(1 - \frac{aI}{I_e}\right)$$

$$\text{or } = 100\left(1 - \frac{i}{I_e}\right).$$

It is necessary to make sure that the restricted earth current is in excess of the highest feeder overcurrent relay setting on the system if overcurrent protection only is provided and it is desired to protect against earth faults as well as phase faults. If the feeder protective gear embodies earth leakage protection then a much smaller current could be permitted to pass through the resistor.

Assuming it is necessary to have a fault current of 400 amps. on a 33 kV. system to ensure operation of the protective equipment, then the required earthing resistor should have an ohmic rating of :—

$$R = \frac{V}{I_e} = \frac{33{,}000}{400 \times \sqrt{3}}$$
$$= 48 \text{ ohms.}$$

The protective transformers for the circulating current system have a ratio of 800/5 and the relay has a fixed setting of 0·2 amp. and the sensitivity is approximately 70 amps. with an impedance of 75 ohms. The full load current of the alternator is 650 amps. so

that the relay setting $a = \frac{70}{650}$ 100 per cent.

$$= 10{\cdot}7 \text{ per cent.}$$

$$\text{Percentage of winding unprotected} = \frac{100\, a\mathrm{I}}{\mathrm{I}_e}$$
$$= \frac{100 \times 70 \times 650}{400 \times 650}$$
$$= 17{\cdot}5 \text{ per cent.}$$

$$\text{or} = \frac{100\, \mathrm{R}i}{\mathrm{V}} = \frac{100 \times 48 \times 70 \times \sqrt{3}}{33{,}000} = 17{\cdot}5$$

$\therefore$ Percentage of winding protected from the end remote from the neutral point $= 100 - 17{\cdot}5$ $= 82{\cdot}5$

$$\text{or} = 100\left(1 - \frac{i}{\mathrm{I}_e}\right)$$
$$= 100\left(1 - \frac{70}{400}\right)$$
$$= 100 - 17{\cdot}5$$
$$= 82{\cdot}5 \text{ per cent.}$$

If the full load current is allowed to pass then the figures are as follows :—

Full load current $= 650$ amps.

Out of balance current $= 10{\cdot}7$ per cent. of $650 = 70$ amps.

$$10 \cdot 7 \text{ per cent. of phase voltage} = \frac{33{,}000 \times 10 \cdot 7}{\sqrt{3} \times 100} = 2{,}040 \text{ volts.}$$

$$\text{Neutral earthing resistance} = \frac{2{,}040}{70} = 29 \cdot 2 \text{ ohms.}$$

Percentage of winding unprotected = 10·7.

The Merz-Price circulating current relays are set to operate on a 10·7 per cent. out of balance current, *i.e.*, if the sum of the currents in the three phases is not zero, but has an out of balance of 10·7 per cent. of the full load current, the relays will operate on the occurrence of such an out of balance. To produce this out of balance current requires a fault voltage of 10·7 per cent. of the phase to earth volts, which means that the stator winding below the 10·7 per cent. value will not be capable of producing a voltage high enough to operate the relays and is therefore unprotected.

Another 30 MW, 33 kV. (Fig. 515) turbo-alternator with auxiliary unit transformer has the following protective apparatus :—

Merz-Price 3-pole relay with two outer poles having normal setting of 1 amp. and centre pole (earth leakage) 0·05 amp. Unit transformer—3-pole overcurrent relay with 100 per cent. plug, 20 secs. and 0·5 time multiplier.

Single pole restricted earth leakage relay 40 m.a.—instantaneous (approx.) protection afforded.

90 per cent. of stator windings protected against phase faults.

85–90 per cent. against earth faults on alternator.

100 per cent. on the unit transformer against phase and earth faults.

Suppose there are three sets in a station each having different outputs, 1 × 25 MW, 1 × 30 MW and 1 × 50 MW, all operating at 11 kV. and 0·8 power factor. Assuming a relay setting of 0·5 amp. ensures stability and that the current transformer ratios are respectively 340/1, 400/1 and 660/1.

Primary out of balance current in 25 MW set = 340 × 0·5
= 170 amps.
" " " " 30 " " = 400 × 0·5
= 200 amps.
" " " " 50 " " = 660 × 0·5
= 330 amps.

The neutral earthing resistance for the largest set will be given by :—

$$R = \frac{V}{I_e} = \frac{11{,}000}{3{,}280 \times \sqrt{3}} = 1 \cdot 93 \text{ ohms.}$$

The unprotected portion of winding $= \frac{iR}{V} \times 100$ per cent.

" " " " " (25 MW set) $= \frac{170 \times 1{\cdot}93 \times 100}{6{,}350}$

$= 5{\cdot}2$ per cent.

" " " " " (30 MW set) $= \frac{200 \times 1{\cdot}93 \times 100}{6{,}350}$

$= 6{\cdot}1$ per cent.

" " " " " (50 MW set) $= \frac{330 \times 1{\cdot}93 \times 100}{6{,}350}$

$= 10$ per cent.

This assumes that the neutral resistor is designed to pass the full load current of the largest set although the earth fault current is often limited to a much smaller figure than this in practice. The current rating of the resistor usually varies between 400 and 2,000 amps., the latter being used on very large networks. There are various time ratings for such resistors, 15 seconds, 30 seconds and 1 or 2 minutes being quite usual. The earthing resistor may be either of the metallic, carbon powder or liquid types, the latter being used frequently due to its low cost. The most satisfactory resistor for main earthing is the liquid type as it is non-inductive and has a low surge impedance. The electrodes of the latter type appear to be better in the form of vertical cylinders in place of the horizontal plate type. The current density should be kept within reasonable limits if trouble-free operation is to be ensured. The resistor should also be capable of carrying the triple-harmonic currents. On measuring the current flowing through the neutrals of two different makes of 33 kV. alternators the following maximum figures were noted :—

No. 1 set	23 amps.—48 ohms.
No. 2 set	15 amps.—29 ohms.

Liquid earthing resistors have a negative temperature-coefficient and should have ample capacity if the danger of the liquid boiling away is to be avoided. A small reactor (harmonic limiting reactor)

in series with the resistor enables a smaller resistor to be used, and the reactor will limit the triple-harmonic current without affecting the 50-cycle fault current or the normal operation of the protective gear. This reactor is specially designed and does not affect the

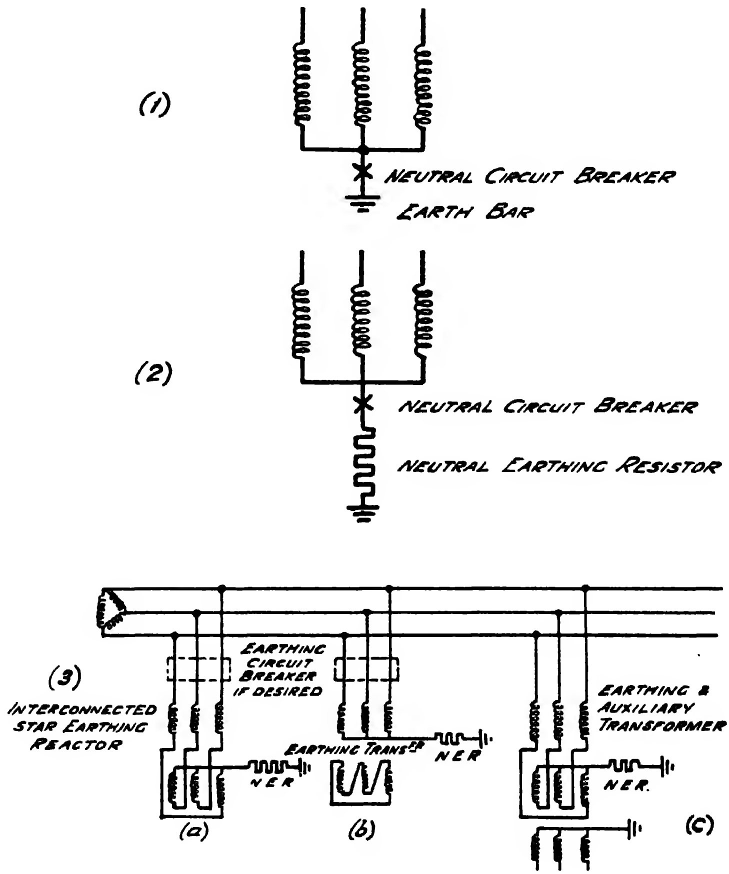


FIG. 526. Neutral Earthing Systems.

normal current due to system faults. As a guide, data relating to a 30 MW, 33 kV. reactor are given :—Reactor designed to carry a full-load current of 650 amps. for 30 seconds and also to carry 15 amps. at 150 cycles per second and choke 500 volts. Reactor of the oil-immersed metal-clad type with cable boxes.

The inductance (reactor) in the earth circuit of each alternator

has an impedance of $2\pi fL$ to 50-cycle currents and an impedance of 3 $(2\pi fL)$ to 150 cycle currents (third harmonics). An alternative could be adopted by using a capacitor (capacitance C) and reactor (inductance L) in the earth circuit. For currents of normal frequency the impedance is $2\pi fL - \frac{1}{2\pi fC}$ and for third harmonics $3(2\pi fL) - \frac{1}{3(2\pi fC)}$. If the capacitance C and inductance is arranged so that $2\pi fL = \frac{1}{2\pi fC}$ (resonating), then the impedance to short-circuit and other currents of normal frequency is zero and to third harmonic currents it is $3(2\pi fL) - \frac{1}{3}(2\pi fL) = \frac{8}{3}(2\pi fL)$.

This impedance can be raised to any value without affecting the short-circuit currents while the third harmonic currents which are the result of a slight difference of voltage will be for all practical purposes eliminated.

Heaters are usually fitted to the liquid type of resistor to prevent freezing, about 6 kW. being sufficient for this purpose. The turbine condensate or distilled water is suitable for filling up, soda being added as required to obtain the desired resistance. A correction curve is provided by the manufacturers so that due allowance can be made for temperature variations. The resistance may be measured by passing A.C. through the resistor, the voltage drop and current being noted.

The earthing equipment will vary according to the conditions obtaining but generally includes a circuit-breaker and resistor together with neutral cable and connections. The neutral earthing layouts included represent some of the latest practice. The determination of the sizes of neutral cables which may be required in a station are items of importance. If a 50 MW, 13·5 kV. set is connected direct to a 66 kV. step-up transformer the reactances of each being 15 and 10 per cent. respectively, then :

$$\text{Short circuit MVA (before transformer)} = \frac{50{,}000 \times 100}{0{\cdot}8 \times 15 \times 1{,}000} = 416$$

and the corresponding current is 17,800 amps.

Using the formula $T = 0{\cdot}005 \left(\frac{I}{A}\right)^2$ (for copper conductors).

Where T = temperature rise per second in ° C.

A = sectional area of conductor in mm².

Assuming maximum permissible rise in temperature to be 150° C. and the time allowed 15 seconds, then temperature rise per second will be 10° C.

Substituting we have

$$10 = 0{\cdot}005\left(\frac{17{,}800}{A}\right)^2$$

$$A = \sqrt{\frac{0{\cdot}005 \times 17{,}800^2}{10}}$$

$$= 400 \text{ mm.}^2$$

$$\text{or } = \frac{400}{645} = 0{\cdot}63 \text{ sq. in. (the alternator neutral).}$$

The nearest standard cable would be chosen as regards both sectional area and voltage since the latter would not be of importance in this case. Where this neutral is taken to earth through a voltage transformer (alarm) it will be appreciated that the cable or copper bar should be insulated up to this point. It is possible to get arcing on the uninsulated length of neutral after the transformer, and in such cases it may be advisable to insulate throughout. The earth fault current would be limited by the impedance of the alarm transformer, in which case the size of the neutral could possibly be reduced. If an earthing resistor is used then the size will be determined by the maximum current passing and the insulation will be in accordance with system voltage.

The size of the step-up transformer neutral can be estimated in a similar manner. In this case, however, the earth-fault current flowing will be limited to some predetermined value; a figure of 1,000 amps. will be taken for the purpose of calculation.

Allowing the same temperature rise as before, we have

$$10 = 0{\cdot}005\left(\frac{1{,}000}{A}\right)^2$$

$$A = \sqrt{\frac{0{\cdot}005 \times 1{,}000^2}{10}}$$

$$= 22{\cdot}4 \text{ mm.}^2$$

$$= \frac{22{\cdot}4}{645} = 0{\cdot}035 \text{ sq. in.}$$

The nearest size cable would be chosen, but it would have to be insulated to withstand a voltage of $66/\sqrt{3}$, *i.e.*, 38 kV. the phase voltage.

The ohmic value of the earthing resistance is

$$= \frac{V}{I_e} = \frac{38,000}{1,000} = 38 \text{ ohms.}$$

The neutral circuit-breaker is designed to carry the current limited by the earthing resistor and the rupturing capacity should be such as to meet all possible conditions of operation. Cases are on record where the neutral circuit-breaker has failed to clear a fault and been destroyed causing a fire in the switch house. The maximum value of the MVA which a neutral circuit-breaker may be called upon to clear will depend on the method of earthing employed.

Three usual methods of earthing are :—

(1) *Dead Earth System.* With this system the maximum voltage a conductor may have above earth is $\frac{E}{\sqrt{3}}$, and as an earth fault is equivalent to a short-circuit on one phase, the earth current may attain a value equal 1·5 times the symmetrical short-circuit current of the system. The maximum possible fault MVA to be dealt with by the neutral circuit-breaker would be one-half of the alternator 3-phase symmetrical short-circuit MVA. The 1·5 current factor represents the worst asymmetrical fault condition possible, and as the impedance of the earth path would probably reduce this to a value very near the symmetrical 3-phase short-circuit current, the maximum possible short-circuit MVA for the circuit breaker to clear would be one-third of the symmetrical short-circuit MVA of the largest turbo-alternator to which it may be connected.

(2) *Resistor or Reactor Earth System.* In this case the maximum voltage between phases which such a resistance or reactance on a 3-phase circuit would be required to withstand will be the phase voltage and this would occur when one phase became dead earthed. The maximum possible fault MVA which the neutral circuit-breaker may be required to clear will be $\frac{E}{\sqrt{3}\,.\,10^6} \times$ current rating of neutral resistance or reactance.

Particulars of two typical equipments are given :—

Alternator MW—kV.	Single Phase O.C.B. MVA—kV.	Resistor Current Amps.
30–33	100–22	650
30–33	100–22	400

(3) *Transformer Earth System.* When it is necessary to obtain an earth point on a transformer-fed system it is usual to provide an artificial neutral point by means of special auxiliary equipment. This may be an interconnected-star earthing compensator or reactor or, alternatively, a star-delta transformer. With these methods the 3-phase neutral-earthing circuit should be designed to withstand the maximum short-circuit MVA which may be expected from the largest alternator on the network. In most cases such a circuit-breaker is not included, the connections being made direct to the main circuit.

Typical earthing arrangements are shown in Figs. 523 to 528.

Earthing Connections. The size of earthing conductors should be based on the maximum earth current flowing under fault conditions, also bearing in mind the necessary mechanical rigidity; one authority has recommended the following :—

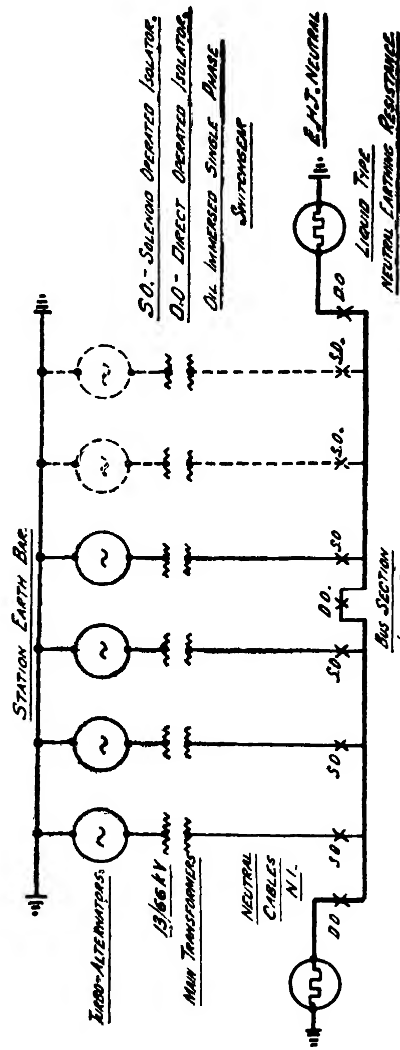


FIG. 527. Neutral Earthing System for 300 MW Station.

(1) For systems earthed through a resistance the section should be based on the maximum earth fault current flowing for thirty seconds. With a 250° C. rise in temperature the current density for this condition is 22,000 amps. per square inch.

(2) For systems solidly earthed, the main earth bar should be based (in the absence of a definite value for the maximum short-circuit) on a current corresponding to the interrupting capacity of the switchgear for one second,

with a temperature rise of 250° C. The current density for this condition is 120,000 amps. per square inch.

In general 20,000 amps. can be taken as the maximum current that stub earthing connections can safely carry, due to joint resistance, etc., and if the fault current is in excess of this, additional earthing connections should be used. In the case of isolated apparatus, the stub connections can be $1\frac{1}{8} \times \frac{1}{16}$ in. copper, provided that there is no objection to the possibility of their burning off.

In this case, the apparatus must be so located that, in the event of the connection being burnt off, there is no danger to life or possibility of fire.

(3) The voltage drop along an earth bar under fault conditions should not exceed 10 volts for resistance earthed systems or 50 volts for solidly earthed systems.

If the voltage difference between the main or stub earth bars and earthed metal work which they touch or pass is greater than 10 volts, the bars should be bonded to, or insulated from, the metal to prevent arcing under fault conditions.

A case is on record where a system had partially lost its main earth connection and a heavy fault took place during this period, causing arcing and severe burning of iron fences, cables, sheaths, pipes, etc.

The only unearthed electrical equipment is the alternator outboard bearing and exciter pedestal.

Some idea of the details required for a station with 30 MW sets are given below :—

Earthing Circuit	Area sq. in.	Short Circuit Current amps.	Time Period secs.
Main copper bar, $2 \times \frac{1}{4}$ in.	0·5	46,000 14,500	1 10
Auxiliary copper bar, $1\frac{1}{4} \times \frac{1}{8}$ in.	0·156	14,000 4,500	1 10
T.R.S. cable	0·4	37,000 11,500	1 10
T.R.S. cable	0·2	9,000 3,000	1 10
Lead-covered cable	0·1	9,000 3,000	1 10
P.B.J. cable	0·225	2,000 650	1 10
C.I. plate electrodes, 4×4 ft.	4608	7,000 2,000	1 10

Full details concerning one power station are given in *Eng. Bulletin* No. 269/70, Siemens Bros. & Co. Ltd.

Earth Plates. The connection to earth is usually made by means of a special copper or cast-iron earth plate or alternatively cast-iron pipes buried in a bed of coke below the permanent water level.

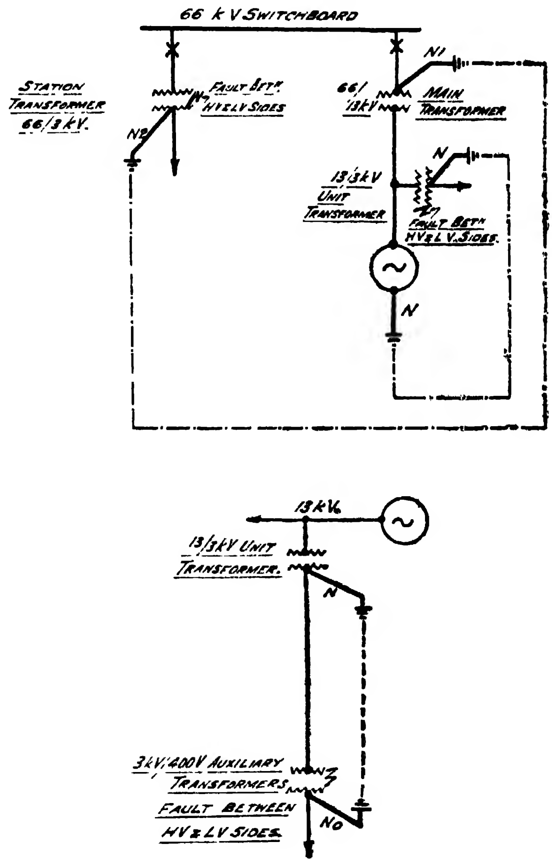


FIG. 528. Neutral Earthing Connections for Station and Unit Transformers.

Where permanently moist ground cannot be ensured a supply of water should be made available so that periodic watering can be done. The value of contact resistance or resistance of the earthing system should be as small as possible and this should be checked from time to time.

Cast-iron earth plates should not be less than ½ in. thick and

about 4 ft. square, strengthened by webs as necessary or alternatively of sufficient lengths of 6-in. cast-iron pipes, not less than ½ in. thick to give an equal total surface of coke in contact with the ground. The several plates or pipes should be buried at a depth to ensure that they are always surrounded by damp earth, and placed vertically and be surrounded with a layer of finely broken coke at least 6 in. thick. All coke used for this purpose should pass a ½-in. mesh. The connections from the main earth bars to each earth plate are made by bonding bare copper conductors or alternatively lead-covered cables (partly stripped) into two separate bosses cast on the plate or pipe for this purpose. Buried tough rubber sheathed cable has also been used. Precautions should be taken for protecting the copper conductors and bonds from corrosion at the joints and those underground. The number of earth plates or pipes will depend chiefly upon the resistance of the earthing system considered to be suitable.

The specific resistance of soils varies considerably due mainly to moisture content and it is rather difficult to forecast the value with any degree of accuracy. It is advisable to test the resistance of any earth electrode when it is first installed.

Use can be made of the "four electrode" method with 4 ft. driven rods at about 20 yd. intervals to carry out preliminary earth tests in the area allocated to the main earth plates. In one case the resistance indicated on the Megger Earth Tester was 0·12 ohm which gave a soil resistivity of the area at about 3 ft. deep of 1,380 ohms/cm.

As a guide some usual values of specific resistance are given :—

Material.	Specific resistance in ohms—cm.³
Ashes	350
Coke	20–800
Garden earth, 50 per cent. moisture	1,400
,, ,, 20 ,, ,,	4,800
Clay coil, 40 per cent. ,,	770
,, ,, 20 per cent. ,,	3,300
London clay	400–2,000
Very dry clay	5,000–15,000
Sand, 90 per cent. moisture	13,000
,, normal moisture	300,000–800,000
Chalk	5,000–15,000

The various regulations relating to earthing should be perused before making a decision for any particular condition. Old pump

bedplates together with cast-iron pipes have been used with good results. The use of retort carbon coke from retort linings has been suggested as being preferable to ordinary coke since it is almost free from sulphur. Tests taken, however, usually show but little difference.

One specification states that the resistance from the electrodes (earth plates) to any point of the earthing system should not exceed 1 ohm.

Relays. All relays should be of sound and simple design and of robust construction. Relays are of the instantaneous, definite-time limit, and inverse-time limit types.

Relays generally have a flag indicator on each pole, the indicator and relay operating coils being connected to the negative pole of the tripping battery to minimise the effect of electrolysis. Points requiring careful attention in relay design are: bearings, contacts, movements and insulation.

Bearings may be grouped into four classes:

(1) Point pivots, (2) Jewel bearings, (3) Knife edges, (4) Plain bearings. Hardened silver-steel points with pivot screws appear to be satisfactory and brass pivot screws can be used, but are unable to carry much load without wearing and causing friction. Stainless steel pivots are not very successful as they do not harden properly.

The advantages of point pivots are cheapness and the large angular travel possible. The friction on plain point pivots is less than that on plain bearings but greater than on jewel bearings or knife edges. A well-designed jewel bearing is one of the most essential features to be considered, especially if considerable angular movement is required. When a relay is required to operate with a small difference in force though subject to considerable total forces, or which may have to withstand large forces, a knife-edge bearing should be used.

The knife edges are of hardened steel and the advantages of this type are: small friction and robust construction. The disadvantages are limited angular travel and cannot be used where reversible forces are encountered excepting in beam relays.

Plain bearings are suitable only for rough relays, where the power is considerable. Difficulty is experienced in aligning.

Three common types of contacts are: platinum, tungsten, silver, and silver copper, although others are in use. Platinum is satisfactory particularly if a wiping action is used and the contact pressure is not nearly as great as that required with tungsten. The latter

require a wiping action or, alternatively, a heavy contact pressure such as that obtained by the wedging action of a falling weight. Silver is mostly used for delicate relays. A special form of contact consisting of a number of platinum wires wiping over each other has given satisfactory service. Under equal conditions a circuit-closing device is better than a circuit-opening device because it makes contact with the whole force of the moving part while the circuit-opening relay, particularly if opening is slow, may give trouble due to pitting and arcing at contacts.

The movements used in relay construction are: horse-shoe, constant air gap, solenoid and induction types. The first is generally employed for relays of comparatively rough constructional features, where the operating power is large. The constant air gap movement usually requires a little extra experimental work. If the air gap in the magnetic circuit remains constant the torque is proportional to the rate of change of the area of the pole face and by shaping the armature which is attracted into a gap in the magnetic circuit, the force of attraction can be made to vary in any desired manner. The solenoid movements are unreliable in operation, sticking of the plungers being a common trouble. The induction disc movements are suitable for watt-meter relays and are frequently adopted for overcurrent and earth leakage relays.

The use of moulded insulations has facilitated relay design and construction, the standard insulations used for electrical work being adopted.

The Inverse-Time Over-current Relay is employed for standby overcurrent and earth leakage protection on alternators, and for the protection of works' auxiliary feeders and transformer services. It is made in two types: (1) with a definite minimum time delay of 0 to 2 seconds, which is adjustable, and (2) 0 to 4 seconds, this type being used for alternators where a larger delay is required to obtain discrimination. The relay has two controls, a current plug setting (Pm) and a time-setting multiplier (Tm). The current plug settings range from 50 to 200 per cent. in steps of 25 per cent. for overcurrent relays and 10 to 70 per cent. in steps of 10 per cent. for earth-leakage relays. The time multiplier ranges from 0 to 1·0 in steps of 0·05. The current plug setting alters the number of turns on the relay coils and hence alters the torque on the disc if the relay is not saturated. In this case the current plug affects the time of operation as well as the pick-up current. The plug setting (Pm) alters, in effect, the current transformer ratio.

Thus a 400/5 transformer operating a relay with a plug setting (Pm) of 50 per cent. is equivalent to a 200/5 transformer operating the same relay with a plug setting of 100 per cent. The pick-up current is that at which the relay starts to move. A 5-amp. relay set at 100 per cent. has a relay full-load current of 5 amps. and a pick-up current of about 1·3 times this, *i.e.*, 6·5 amps. Similarly at 200 per cent. the full-load current is 10 amps. and pick-up current 13 amps. This ensures stability at full-load current. The relay characteristic curve is given as a time/plug-setting multiplier curve where

$$\text{Plug-Setting Multiplier (P.S.M.)} = \frac{\text{Fault current in relay}}{\text{Relay full-load current}}$$

$$= \frac{\text{Fault current in primary of C.T.}}{\text{C.T. full load} \times \text{plug setting per cent.}} \times 100$$

A relay connected to a 400/5 transformer and set at 100 per cent. would have a full-load primary current of 400 amps.; if set at 150 per cent. full-load current would be 600 amps. With a primary fault of 2,000 amps. the P.S.M.'s would be 2,000/400 and 2,000/600 respectively. If the fault current, plug setting and current transformer ratio are known the P.S.M. can be determined and a time obtained from the Time/P.S.M. curve (Fig. 529). The time setting (Tm) usually moves the initial position of the disc so that the length of travel to close the contacts is reduced. If a Time/P.S.M. curve is available for a time setting of 1·0 it is necessary to multiply the results taken from this curve by the time-setting multiplier used. Thus, to calculate the time of operation of a relay the following must be known :

(1) Time/P.S.M. curve for relay.
(2) Current plug setting (Pm).
(3) Time setting (Tm).
(4) Fault current.
(5) Current transformer ratio.

An important feature of this relay is the plug-setting bridge which allows the plug to be withdrawn while the relay automatically adopts the setting that it would have if the plug were inserted in the centre tap position. The setting may thus be changed on load without opening the current transformer secondary circuit and without the use of a spare plug. Another advantage is that the operation of the relay is assured even if the plug is inadvertently left out (100 per cent. setting). The percentage values marked on the current

setting bridge refer to the current transformer rated current, and at these values the relays remain inoperative. With currents 30

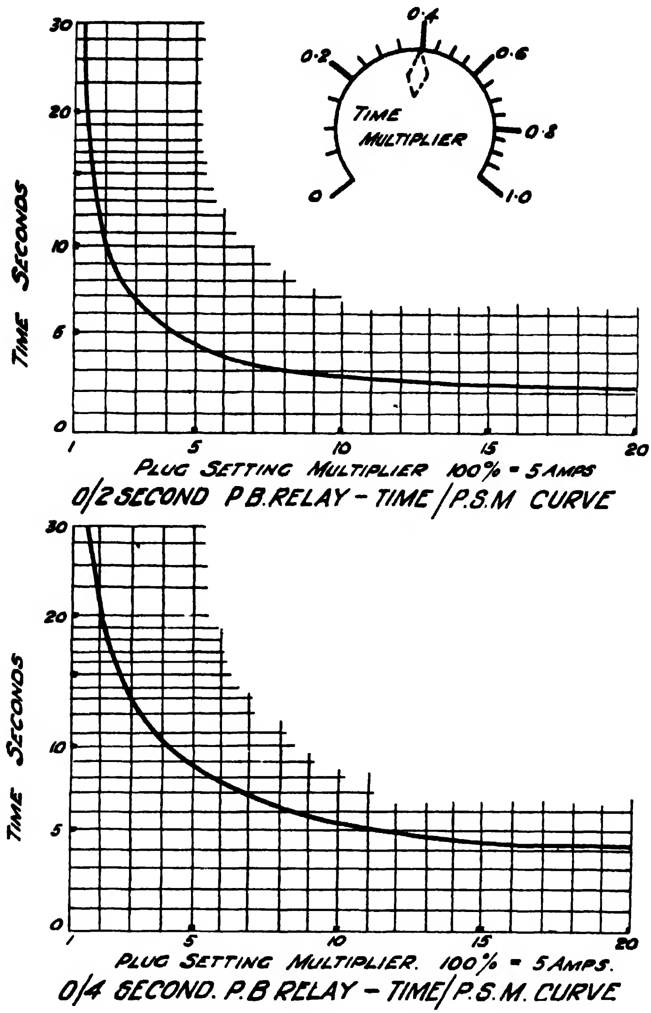


FIG. 529. Relay Time Curves.

per cent. in excess of the setting value for any setting (*i.e.*, 1·3 S, where S is the setting) the relays operate in thirty seconds when the time multiplier is 1·0 (*i.e.*, the maximum) and in proportionately shorter times for other multipliers.

For example, a relay operating from a current transformer of ratio 800/5 and set at 100 per cent. on the setting bridge would, as shown by standard curve, operate in thirty seconds with 1,040 amps ($= 1\cdot3 \times 800$ amps.) when the time setting pointer is set at 1·0. Similarly, with 1,300 amps. ($= 1\cdot62 \times 800$ amps.), the relay operates in twenty-five seconds.

It is advisable to ascertain the sustained fault current when this protection is applied so that the plug setting is chosen to give the desired secondary current for relay operation. Some idea of the feature mentioned will be obtained from the following data relating to turbo-alternators :

M.C R. Output—MW.	10	20	30
Instantaneous short circuit current (peak symmetrical) approx.—amps.	11,500	23,000	4,300
Time to change from instantaneous to sustained short circuit current—secs. approx.	2 5	2·5	2·5
Reactance—per cent.	12·5	12·5	20·0
Voltage—kV.	6·6	6·6	33·0
Voltage regulator-out sustained fault current—amps.	1,750	3,250	900
Voltage regulator-in sustained fault current—amps.	2,250	4,500	1,300

A great deal will depend on the excitation obtaining and the temperature condition of the machine.

Neutral Inversion. The danger of switchgear, transformer and cable breakdown due to an over-potential caused by neutral inversion may be present in any type of electrical equipment where the conditions are suitable. Neutral instability is a complex form of resonance and is liable to occur where a 3-phase alternator, transformer or other apparatus with windings and connecting cables of appreciable capacitance to earth is earthed through the neutral point of an instrument transformer. In other words, the characteristic condition for neutral inversion is that the system is earthed only through a saturated reactance such as instrument voltage transformers in parallel with capacitance.

Neutral inversion may be eliminated in several ways, some of which are :—

(1) Earthing the system either directly or through a low value of resistance or reactance.

(2) Isolating the neutral point of the voltage transformer.

(3) Connecting a loading resistance across the secondary winding of the voltage transformer, in addition to the normal burden.

(4) Connecting a damping resistance in the open delta of a tertiary winding included in the voltage transformer for this purpose.

(5) Connecting a surge arrestor between the neutral or terminal points of the alternator and earth.

(6) Connecting a spark-gap between the alternator neutral point and earth.

(7) Connecting a resistor of the ceramic type between the alternator neutral point and earth.

(8) Installation of a voltage transformer designed with a low saturation in the magnetic circuit at normal voltage.

(9) Earthing system permanently through a high value of resistance.

The following particulars relate to a draining resistance of 300 ohms used with a 30 MW, 33 kV. turbo-alternator.

MW	P.F.	kV	Volts	Current
20	0·90	32·3	500	1·7
25	0·88	32·1	590	2·0
30	0·95	33·0	700	2·3

Lightning Protection. The protection of plant and buildings against lightning appears to have been a very much neglected section of the works. Overhead lines radiating from a station usually have a reasonable length of cable between the terminal point and the switchgear and this protects the plant against surges. Choke coils and lightning arrestors are common on small overhead lines, although the effectiveness of choke coils for this purpose has been the subject of research in recent years and results appear to indicate that no useful purpose is served by their inclusion. Surge absorbers are frequently used for main sub-station service and appear to be proving satisfactory. Unlike other arrestors it provides no conducting path, energy radiating from it into the atmosphere in the form of heat. It consists essentially of a coil of copper conductor suitably insulated and connected in series with the line. Surrounding this coil and placed in a strong part of its magnetic field is a metal shield, usually of iron or stalloy, which forms the energy dissipator and which is connected to earth.

Experience has shown that lightning is not erratic in its behaviour

for investigations after damage have proved that it would be expected under such conditions. Complete protection of buildings both internally and externally depends upon the efficient discharge of all statically charged metals through pre-arranged conductors and not through any casual paths, such as pipes or structural steelwork.

Although the potential of a conductor is uniform at all points, it by no means follows that the electrons distribute themselves in a layer of uniform density along its surface. In an irregularly shaped conductor the electrons tend to crowd or concentrate into the more pointed portions of the surface. To prevent such concentrations on high voltage conductors it is desirable to avoid corners, points, etc., and in cable work (joint boxes and sealing ends) stress cones are used. The surface density of the charge on a conductor is a maximum on the most pointed portion of its surface. Where the surface comes to a sharp point this crowding may be of such intensity that the surrounding air acquires some of the charge and is repelled from the point along the lines of force between the conductor and the particles of air. This is usually referred to as "brush discharge," or electric wind. Use is made of such points (action points) where a quick discharge of electricity is required.

The chief features requiring attention when designing a lightning protection system are :—

(1) To choose the points which are vulnerable, to which the conductors should be taken.

(2) To decide which structural members of the building or its equipment should be connected to the conductor system and which should not be connected.

(3) To select the most suitable routes for the conductors between the elevation rods and the earth plates keeping in mind the metal objects mentioned under (2).

So far as vulnerability is concerned it is obvious that the highest and most projecting parts of the buildings call for protection. Brick and concrete chimneys are the usual items to which the elevation points are fixed. Where the buildings are physically separated and no prominent features exist, gables form vulnerable points, and where there is more than one gable, all should be protected. Sub-erections on high parts of a building, particularly flagstaffs, lighting fittings and the like, are spots likely to be struck and the protection should always be extended to include these. The metals used on or in a building include gutters, lead flashings, structural steelwork and ventilators, and these should all be connected to the conductor

system if a conductor passes within a few feet. Steel and iron ladders, stairways and water pipes should be likewise considered.

The lightning protection system should be prepared at an early date in the design stage, for in this way the constructional details of a building can be arranged to provide the best possible routes for the conductors relative to all other sections of the work. Many bends may be avoided by including slots in copings and mouldings and so obtain straight runs for the conductor tapes. It is undesirable to add self-inductance to a lightning conductor circuit as this may tend to excite potentials by induction in adjoining metals not forming part of the intended conductor circuit.

The inclusion of bends may result in flash-over and tearing away of the conductor from its fixings.

Lightning discharge currents are of high frequency and rather than traverse a bend of low resistance will jump across a path of higher resistance. In the case of a lightning discharge a bend in a tape around masonry will provide a higher impedance than that of the masonry. This may result in destruction of those parts of the building coming within such bends. The elevation rods or spears vary in length from 3 to 6 ft. and are placed at the salients of the buildings and also on such isolated points as flagstaffs or beacons even if the latter are at a lower level. Chimney stacks are probably better protected by a coronal band fitted with several short points, these being bonded together and earthed through copper tape. The area protected by an elevation rod is difficult to estimate, but as a rough guide it is usual to assume the area protected to be that of a circle of diameter equal to the maximum height of the system. Cooling towers are sometimes provided with lightning conductors, but these appear to be unnecessary if the towers are in continuous operation, when vapour will always be flowing from the tops.

High conductivity copper tape is generally used for lightning conductors, the section depending on the route length. Copper tapes for lengths up to 80 ft., $\frac{3}{4} \times \frac{1}{8}$ in.; 80 to 120 ft., $1 \times \frac{1}{8}$ in.; 120 to 180 ft., $1\frac{1}{4} \times \frac{1}{8}$ in.; 180 ft. and over, $1\frac{1}{2} \times \frac{1}{8}$ in. are in use.

The tape is available in 300 ft., 400 ft. and even up to 700 ft. lengths and should, wherever possible, be fixed without joints. At the top of chimneys it is advisable to double the copper for a few feet to guard against the corrosive effect of flue gases. Where joints are made they should be riveted and soldered. The tape is fixed direct to the building about every 5 ft. with clamps spiked to the surface with copper or gunmetal holdfasts and nails. Copper

cable is not recommended by British authorities, although Continental and American practice favours this conductor. It is contended that the interstices between the wires form a lodgement for dirt and chemicals from the air which in due course results in corrosion.

Gable ends and roof ridges may require separate protection with "aigrettes" or short air terminals. The conductors are connected to a final earth connection which is taken to an earth plate. Earth plates are of substantial gauge copper $\frac{1}{8}$ to $\frac{1}{4}$ in. of not less than 3 ft. square and buried at a depth of about 5 to 6 ft., depending on the moisture of the surrounding ground. The earth plate is buried with its plane surface parallel to the ground and placed at a distance of 5 to 15 ft. from the footings of the building. Special earthing rods are also available. Where practicable and permissible a connection should also be taken to a water main by drilling and tapping a flange of the pipe line and bolting the copper tape up with a brass bolt.

It has been suggested that the lightning protection system should be examined by a specialised engineer in this work every three years. The chief causes of deterioration are corrosion due to electrolytic or chemical action, mechanical damage, and poor joints due to expansion and contraction. Even more important than physical examination in the periodical survey is the general inspection of the site and buildings to note subsequent additions which may adversely affect the original protective system. For the preservation of the conductors against weather various coverings have been used, but common tar appears to give good service.

Testing may be carried out by a hand generator and low reading ohmeter, or by a bridge and batteries, both for conductor continuity, conductivity and resistance to earth. A dry battery of a few volts is suitable and a reading of about 4 to 6 ohms at a distance of 10 to 12 ft. away is usually satisfactory. Where a gap is required for testing it takes the form of an isolating link mounted in a straight line and enclosed in a water-tight case. Caution is needed when opening the earth circuit of a lightning conductor for it is seldom that there is no discharge passing, whatever the weather, and high potentials may be reached across the link. One method of testing chimney conductors is to run one tape solid from the coronal band to earth and another on the opposite side of the stack, but having a gap closed by a test link. With the link open and the test gear inserted it is easy to test up to the coronal band and down to earth on the one side and to the earth plate direct on the other.

The lightning system for one brick chimney 150 ft. high consists of 170 ft. × $1\frac{1}{2}$ in. × $\frac{1}{8}$ in. high conductivity copper tape. The tape is in one length and fixed to the stack every 5 ft. with gunmetal holdfasts spiked with gunmetal nails. The tape is secured to a $2\frac{1}{2}$ × 1 in. solid copper ring at top of shaft 8 ft. diameter, the ring being fixed at the top with muntz metal bolts $\frac{7}{8}$ in. diameter, spaced about 3 ft. apart, batted into cope with lead and having three solid copper spears 3 ft. high by $\frac{3}{4}$ in. diameter, equally spaced round the circle and firmly fixed into the ring. Each spear is tipped with platinum. The conductor tape is taken 5 ft. into the ground at the bottom of the stack and extended to a distance of 25 ft. from the stack base, being riveted and soldered to a copper earth plate. The earth plate is 4 ft. square and $\frac{1}{16}$ in. thick, buried in suitable earth.

The orthodox lightning conductor is not suitable for a power station chimney due to corrosion and the difficulty and costly nature of repairs and replacements which may be found necessary. An exceptionally heavy main conductor system with air terminals made in acid-resisting unpolished bronze is used. The cast finish is extremely hard and not so liable to corrosion as would be the case after machining. The terminals, fixing brackets, tape couplings, and junction boxes are tinned by hot process to afford further protection against acid attack. The high conductivity copper tape in the upper 40 ft. of a 350 ft. 22 ft. dia. reinforced concrete chimney is seamless lead-covered the ends of which are tinned.

The chimney has a cast-iron cap made up of thirty-two sections, all of which are bonded together by lead-covered copper tapes to make them electrically continuous. Six air terminals are interconnected at some 4 ft. from the chimney top by a lead-covered coronal band, the joint between this and the copper tapes from the finials being made by tinned junction boxes. Two down tapes are fitted and at the flue gas duct platform a copper inter-linking tape is provided from which copper bonds are made to the conductor. The down tapes continue from this level to test clamps placed at a convenient height above ground level to facilitate the testing of the separate earth termination as required. For each down tape there are three driven earth electrodes, which it is estimated will result in reaching the water level. The two groups of electrodes are interconnected by a continuous base tape running below ground level. The equipment supplied is generally as follows :—

Air Terminals

Six terminals spaced equi-distant on the circumference of the chimney head, and made from $1\frac{1}{4}$ in. dia. acid-resisting bronze, with solid ball and four subsidiary points. The solid ball slips over the main terminal. Each finial is screwed at the lower end and has an acid-resisting bronze coupling. The overall length is about 7 ft.

Coronal Band

Circular band made from $1\frac{1}{2}$ in. $\times$ $\frac{1}{4}$ in. solid H.C. copper with 0·1 in. radial thick, seamless lead covering, complete with bronze junction box for making an efficient connection where the two ends of the band overlap.

Junction Boxes

Six boxes each secured in position by means of four bronze rag bolts and nuts. Four of these connect the short leads of lead-covered tape $1\frac{1}{2}$ in. $\times$ $\frac{1}{4}$ in. section from the air terminals to the coronal band. The other two boxes connect the coronal band to the down tapes and also the two leads from the cast-iron cap.

Bonds to Cast-Iron Cap

Thirty-two, 12 in. lengths of 1 in. $\times$ $\frac{1}{8}$ in. H.C. copper seamless lead-covered tape, each with two bronze bonds and bronze set screws for bonding the sections of the cast-iron cap. Each bonding strap is shaped to allow for expansion and contraction of the cast-iron sections. Two short lengths, about 6 ft. each, of $1\frac{1}{2}$ in. $\times$ $\frac{1}{4}$ in. lead-covered copper tape with bronze bonds and set screw at one end for connection from the cast-iron cap to down tape junction boxes.

Down Tapes

Two tapes, the uppermost 40 ft. of each made from $1\frac{1}{2}$ in. $\times$ $\frac{1}{4}$ in. solid H.C. copper with seamless lead covering of 0·1 in. radial thickness. The joint between the two tapes is made by tinning the bare copper, riveting and soldering. The down tapes are not continuous from the top of the chimney down to ground level, but to facilitate fixing and testing each down tape is cut at gas inlet ducting platform and also at the test box positions which are some 6 ft. above ground level.

Holdfasts

Bronze holdfasts are provided for fixing the uppermost 40 ft. of lead-covered tape at 5 ft. centres, and for the horizontal run of the coronal band at 4 ft. centres. The holdfasts below this 40 ft. level are of gunmetal fixed at the same centres. Each has a loose cover plate secured by set screws.

Interlinking Tape

At the ducting platform level $1\frac{1}{2}$ in. $\times$ $\frac{1}{8}$ in. bare copper tape is fixed on edge round the inlet chamber, From the test clamps immediately below the ducting a length of $1\frac{1}{2}$ in. $\times$ $\frac{1}{8}$ in. copper is provided with bond and set screw for making direct contact from the ducting into the test clamps.

Earth Terminations

Six $\frac{5}{8}$ in. dia. H.D. solid copper rods 16 ft. long with hardened mild steel spike at one end, are included for connecting the two down tapes with the general mass of earth. Each rod is made up in 4 ft. sections, jointed together by means of high tensile bronze dowels. The rods are provided with mild steel driving heads, and gunmetal connector clamps for joining in parallel each set of three electrodes.

Base Tape

One length of $1\frac{1}{2}$ in. $\times$ $\frac{1}{8}$ in. H.C. copper tape connects the individual earth electrodes and also the two groups.

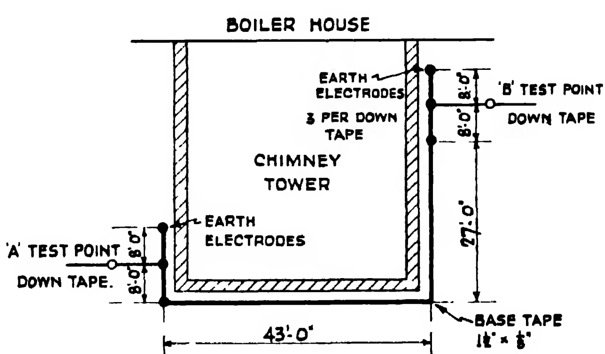


FIG. 530. Lightning Conductor Earth Test.

Test on Lightning Conductor Earth

Referring to Fig. 530 the tests were made at points "A" and "B." An A.C. hand-generated testing set was used to avoid any

electrolyte ground currents which may affect the readings. The interconnecting base tape was not disconnected as it had already been covered in.

Test 1. With " Megger " earth-testing set from "A" to earthing cable on station circulating water system pipe.

Test figures :

1·08—earth resistance and resistance of leads.
0·22—resistance of leads.

0·86 ohm—earth resistance.

Test 2. With " Megger " testing set from point " B " to station earth bar.

Test figures. As in (1).

Test 3. Check test using A.C. volt drop test from point " B " to station earth bar.

Current passing—10 amperes.
Voltage drop —8·6 volts.
Earth resistance—0·86 ohm as before.

These results were considered to be satisfactory. During the construction of the chimney the internal steel scaffolding which proceeded upwards with the shaft was used as a lightning conductor, the base being connected to one of the test boxes. The chimney details are given in Chapter VII, Vol. 1.

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CHAPTER XIX

STATION LIGHTING

THE minimum levels of illumination and the general requirements of lighting, both natural and artificial, are laid down in the Factories Acts, 1937 and 1948 and subsequent Statutory Instruments. The most important feature of a good lighting system is that the resulting illumination should, as near as possible, make up for the lack of daylight. This implies that the lighting should be adequate, steady, evenly distributed and correctly diffused. In view of the conditions prevailing during war, when glass is out of favour, daylight could be eliminated in the power station. A station operates twenty-four hours a day and 365 days a year and daylight is only available for about one-third of the running period. Good artificial lighting is available at cost price, planning problems are easier and capital cost reduced if the need for providing daylight is dispensed with. A certain amount of daylight could be included in the operators' rest rooms, control room, etc., as this does tend to relieve the monotony. The difference between seeing in the daylight and in darkness makes it necessary to provide artificial lighting of a character that will be helpful in avoiding accidents under low illumination intensities. Visibility must be good enough to give a true picture of confronting conditions in time to make decisions for avoiding accidents. The latter is especially applicable to outside yards for coal and ash-handling plants.

The selection of units, their arrangement and spacing in order to obtain an ideal and economical layout for the many and widely varying arrangements are important. Adequate general lighting of the station is essential both inside and outside, supplemented where necessary by suitable local lighting. General lighting could be reduced where local lighting is used.

To obtain evenly distributed lighting it may be thought that this can only be achieved by using a large number of lighting points of suitable power. The number of points should be as few as possible, suitable units being used to obtain a good distribution of light, thereby ensuring reliability of operation, safety, economy and ease of maintenance.

To use small units and place them close together is uneconomical, partly because small lamps have a higher current consumption per

lumen and installation costs are greater. Use has been made of special diffusing glass which permits the use of high intensity lighting without discomfort. The illumination intensity varies for each section of the station and should always be designed for the recommended maximum rather than the required minimum. Lamps depreciate to some extent during use and it is advisable to replace them periodically and not wait until they fail through filament exhaustion. The failure of individual lamps may cause inconvenience and are troublesome to replace, particularly in inaccessible positions. A higher standard of lighting, greater efficiency and better maintenance are obtained if the lamps are replaced on expiration of their useful life. The choice between mercury, tungsten, sodium and fluorescent, and the general arrangement of exterior lighting may often be governed to some extent by local conditions and economics. The requirements of municipal and port authorities, the Ministry of Transport and the railway authorities may all have to be considered.

The economic comparisons of fluorescent and tungsten lighting are sometimes difficult and not always conclusive. The fluorescent lamp on the score of high efficiency and low brightness can be applied with success to many situations in a power station. It is always advisable to provide adequate lighting for emergency services, this being an essential auxiliary.

As the majority of buildings are of brick or concrete, it is advisable to plan the main lighting distribution system as early as possible during the construction period, for in this way alcoves and recesses can be left in the walls for the lighting cabinets, control equipments and associated circuits. Such a scheme gives a pleasing appearance in comparison to protruding distribution boxes and conduits.

Turbine House. The turbine house with its large impressive turbo-alternators is worthy of some refinement in its scheme of lighting for it is usually the show place of the station. The two chief methods of lighting are the overhead and side lighting systems, or a combination of both. The building construction will, of course, be a deciding factor in the system of lighting to be adopted. Where the roof is flat and unglazed, the lighting units should be chosen so that they illuminate both the floor and the roof. This gives the whole house an evenly diffused light, thus eliminating the usual black shadowed ceiling. The desired lighting is obtained by mounting the units on the face of the crane girders and continuing round the end walls at the same level, a further advantage being that the

crane does not obstruct the lighting as is the case with overhead mounting.

As an example, a turbine house 300 ft. long, 80 ft. wide and 70 ft. high from operating floor to ceiling with units placed at a height of 30 ft. above floor level required approximately 85 units, each having a 500-watt gas-filled lamp. Part of this lighting illuminated the ceiling so that the watts per square foot were really halved. A special design of fitting using diffusing glass was used. The resulting illumination appears to have given the desired degree of comfort and proved satisfactory for all working conditions. In the feed pump bay and turbine house basement similar fittings having 300 watt gas-filled lamps are used.

Various types of fittings have been used for overhead mounting, but in practice it is found that a reflector provided with clear or frosted cover glasses (visor-fronts) are more satisfactory as they require less maintenance. A recent installation comprises twin-lamp industrial troughs fitted with 8 ft. 125 watt fluorescent tubular lamps mounted 40 ft. above floor level. The average service illumination is 12 to 14 lumens per sq. ft. Another installation of interest is described in the *Electrical Journal*, May 28th, 1954.

Boiler House. The lighting of boiler houses is by no means easy, for the many galleries, platforms, ducts, etc., present problems which are only overcome by the use of specially designed fittings. A compromise may be made by the careful placing of dispersive reflectors, angle reflectors and bulkhead fittings. In some cases discharge lamps have been used for general lighting over certain sections of the boiler house. Use has also been made of trough lighting on a boiler firing floor in which there are 4–500-watt lamps per trough. The troughs are mounted on the bunker columns, one fitting being placed at the front of each side passage between boilers. The lighting equipment should be of the protected type having either well-glass or dust-tight visor fronts. Aluminium paint assists in lighting auxiliary plant where bulkhead fittings can only be used. Correct mounting positions should be obtained relative to the portions of plant usually requiring inspection and maintenance. These parts should be kept free from glare, but the person making examination should not cut off the light. This applies in particular where it is impossible to give good general lighting. An adequate number of low-voltage plug points should be provided to facilitate boiler inspection.

Control Room. The important features were briefly outlined in Chapter XIV. An extensive laylight of opalescent glass through which the lighting is projected and troughs provided with diffused glass covers to throw the light up to the ceiling are common.

As artificial lighting is almost inevitable in rooms designed to A.R.P. specification, a good standard of illumination is desirable.

The colour of fluorescent lighting closely approaches that of daylight, and this is an important feature when artificial lighting is in constant use, possibly throughout the life of the station. Further, due to the length of the fluorescent tubes, there is a very low intrinsic brilliancy of the light source, and this reduces the possibility of eyestrain compared with the point type of lighting fitting. Fluorescent lighting is more expensive, but energy consumption is considerably less than tungsten filament lamp in enclosed glass fittings. Fluorescent tubing has also been used in conjunction with an overhead laylight using filament lamps. In one control room for a 300 MW station some 200 ft. of tubing is fixed in fibrous plastic cornices, the tubes being curved to the line of the cornice with electrodes turned back to form a continuous line of light. Three tiers of the cornice lighting consists of single white and blue fluorescent tubes for decorative lighting only. The lower section contains a run of some 40 ft. of triple tubing consisting of one red, one green and one blue tube, each colour being separately dimmer controlled by push button operated motor-driven resistance dimmers. The lighting control panel is mounted on the control engineer's desk together with all switches for the colour combinations which can be varied to give the desired effect. This system of colour lighting can be used for demonstration purposes and therefore serves a dual purpose. It is a new development in the lighting field and has the elements of novelty, colour flexibility and economy to make a powerful appeal to lighting sales.

Switch Houses. Good general lighting is necessary.

Outdoor Services. Outdoor transformer and switchgear layouts may be catered for by the provision of adjustable flood-lighting equipments. Flood lighting for yards, roadways, sidings, etc., is usually less expensive, but the glaring character of the lighting is not very satisfactory unless relatively high mounting heights are employed.

In some stations the lighting on the coal-handling plant is all treated as crane work and is supplied at 110 V. centre-tapped, earthed. This approved safety voltage is also used for plug boards

for portable tools which are provided round the station. These are supplied through 5 kVA transformers.

Where stations are in the vicinity of aerodromes it is advisable to provide suitable neon lights on chimneys and special fittings and equipment are available for this purpose. The possibility of providing suitable advertising features should not be lost sight of, particularly where any special buildings can be used. An example of this is where large reinforced concrete cooling towers are installed, and if the site is favourable it is possible to floodlight these towers with great effect. At night a wonderful spactacle is presented and can

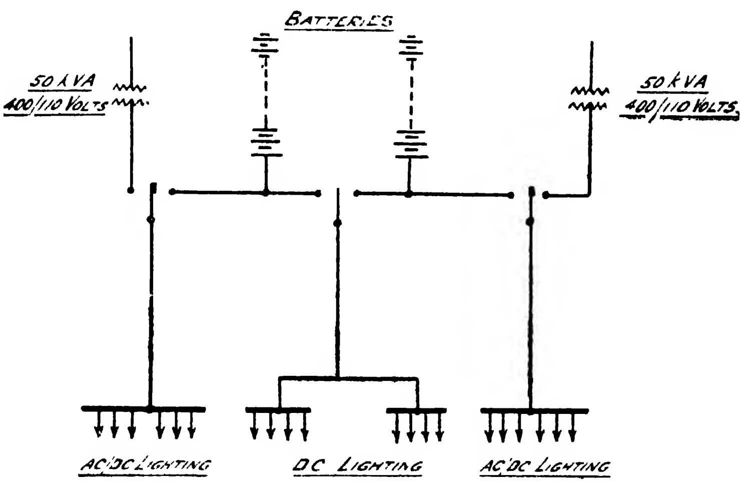

FIG. 531. Combined A.C. and D.C. Lighting Systems.

usually be seen for miles around. Main buildings can also be designed to give effect to floodlighting.

Sources of Supply. For general station lighting, supply from the lower voltage A.C. switchboards or independent lighting transformers is usual. Where single-phase transformers are used the phases should be balanced as near as possible. Figs. 531 to 533 show typical systems. With the marked increase in size of stations, together with the general raising of illumination levels, the lighting load may reach a comparatively high figure.

In some cases the station lighting is divided into sections, each turbo-alternator serving its own section by the provision of an individual lighting transformer and control equipment. A further arrangement is to balance out the lighting, and in the event of the

A.C. supply failing the lighting switch can be changed over to supply one phase with D.C. from the station battery. When fluorescent

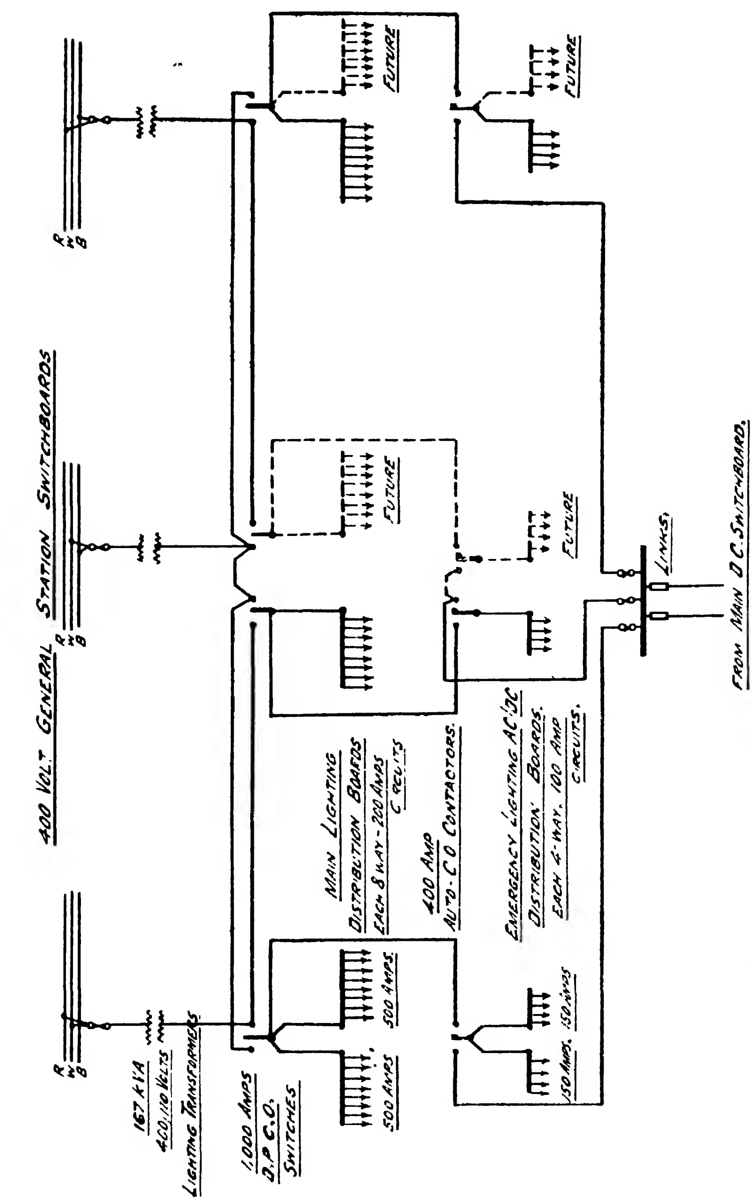

FIG. 532. Lighting Scheme for Turbine and Boiler Houses—300 MW Station (see also Fig. 533).

lighting is installed the supply is taken from three-phase and neutral distribution boxes. Three-phase four-wire circuits supply each row

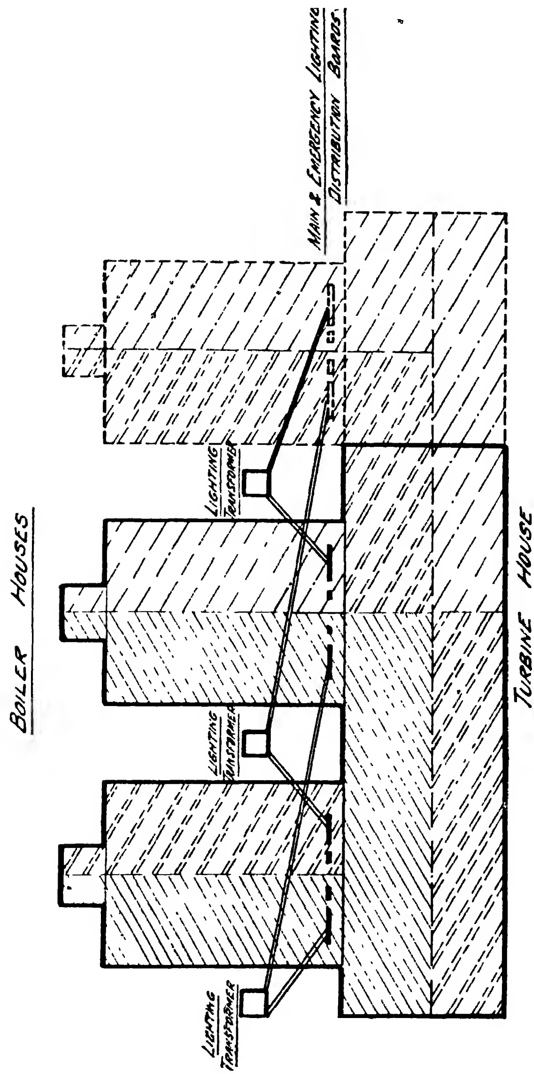

FIG. 533. Plan of Lighting Scheme.

of lights, alternate lights being connected to a different phase to reduce the stroboscopic effect.

The emergency lighting also calls for consideration and present

practice appears to favour the use of D.C. for this service, the supply being taken from a battery. The voltage to be used will be governed by local requirements, but where the D.C. load is reasonably large to auxiliaries such as boiler draught fans, turbine pumps, cranes, etc., it may be that a 480-volt three-wire system would be used. The lighting voltage would then be 240 volts, and that for power 480 volts. Where the D.C. power load is small the battery would normally be 110 volts and the A.C. lighting would be fixed at 110 volts, to be in line with emergency lighting at 110 volts D.C. In this case the voltage of the battery would usually be determined by the voltage required for the switchgear closing and tripping circuits. The standard voltage of 240 volts is suitable and is employed for both interior and exterior lighting. The scheme of lighting adopted should be such that if failure did occur there would be adequate lighting to maintain normal working conditions. For normal lighting this would be met by subdivision of supplies from the various supply units.

A further safeguard is to include a liberal amount of emergency D.C. lighting by providing contactors arranged to transfer the emergency circuits to the battery and re-establish normal conditions when the main A.C. supply is restored.

There are a number of circuits which should be permanently connected to the battery. These include boiler water gauges and instrument panels, turbine gauge panels, switchgear indicating lamps and a portion of the control room. A large proportion of the main lighting will be permanently connected to A.C., change-over to D.C. being arranged for predetermined sections of the lighting only.

In one station the lighting supplies are afforded from 2–350 kVA, 3,300/433 volt transformers on four-wire medium voltage circuits. Separate fuse boards are provided on a ring main feed by these transformers for boiler-house, turbine-house, workshop and administrative block. Emergency lighting is supplied from a 240 V. 400 Ah. station tripping battery, which gives an unearthed supply.

Neutral compensators may be used to give supply to small lighting loads for workshops, laboratories and offices if these are situated some considerable distance from the main lighting boards.

Small double-wound transformers having a secondary voltage of 50 volts are installed for services to hand lamps, the centre points of

the 50 volt windings being earthed. The main lighting supplies, whilst being physically separated should preferably be located within easy reach of each other unless remote control is provided.

TABLE 74. *Lighting Required for a* 300 *MW Station*

Section of Plant	Capacity in kW.
Turbine house	150
Boiler houses	200
Pump house	10
Switch house and control room . . .	50
Workshops and offices	30
General and outside	40
Total	480

TABLE 75. *Lighting Data*

Section of Plant	Lum./sq. ft.	Emergency Lighting as per cent. of Installation
Turbine house	10–15	30–50
Boiler house, firing aisle . . .	10–12	25
,, ,, basement . . .	3–6	25
Conveyor galleries	3–6	25
Coal and ash handling . . .	3–6	25
Switch house	5–8	25–40
Control room	20–30	40–100
Pump house	6	25
Roadways and yards . . .	0·5–1·5	25
Offices and messrooms . . .	6–15	25

This is desirable should the need arise for complete cutting off of all lighting in case of air raids. In view of the latter contingency due consideration should be given to the planning of a station lighting system. A number of lighting points having specially designed lamps invisible from the air could be installed near all important auxiliary plant and operating positions.

Lighting data are given in Tables 74 and 75

CHAPTER XX

COMMISSIONING AND TESTING OF PLANT

THE commissioning and testing of plant after its installation are, broadly speaking, the same in any station in so far as the usual detail tests are concerned. Certain sections of the plant will be tested before commissioning whilst others must be in commission before testing can be proceeded with. Examples of the former are switchgear, transformers, motors and protective gear; the most important items coming under the latter section are the turbo-alternator and boiler plants. On a large new station the number of main contractors, apart from sub-contractors, is often fairly high and one of the essential features is the co-ordination of the various works involved. This linking up is most important as loss of time is possible by concentrating on certain sections of a contract which may not be required until a much later date. The commissioning of a station will vary according to local requirements and in general will depend on whether extensions to existing plant are being made (which may be either at the same or a higher steam pressure and voltage) or if an entirely new station has to be considered. A riverside or a cooling tower station may have to be catered for and each demands special consideration in the starting-up procedure. A contractor, no matter what section of plant or works he is associated with, has to see that each item is installed and working to the satisfaction of the client's engineer. As the majority of the services in a station are motor-driven it is necessary to have a supply available at an early date for auxiliary purposes alone.

Auxiliary Electrical Supplies. If the station is an extension to an earlier section or existing station, anxiliary supplies will be available within certain limits. A new station will entail the provision of a special overhead line service from a distant station, or alternatively the installation of a temporary internal combustion engine generating set. In any case a supply must be available at an early period of the constructional works. Civil engineering and building works contractors require a supply and immediately the turbine house structural work is completed the overhead crane or cranes will have to be erected and put into commission. The

problem of auxiliary electrical supplies must receive careful consideration and every possibility must be taken account of if satisfactory and unimpeded progress is to result throughout the construction of the station. If, in the normal course of events the new station is to be interconnected with one or more other stations, the installation of a transforming sub-station on or near the new site and taking supply from the existing network will be one way of overcoming the difficulty. Here again attention must be paid to the supply available as the existing station or stations may only be of comparatively small outputs, necessitating taking auxiliary supplies at certain low-load periods. As will have been observed from Chapter XVII, the power required for these services in a large station is of no mean order ; further, " direct on starting " of large motors must be considered. Having obtained a supply at the main sub-station the next step is to make a section of the main high-voltage switchgear "alive." From this switchgear onwards the high-voltage cables and works auxiliary transformers must be tested and the corresponding lower voltage station switchboards must be ready for service. The whole of the lower voltage cabling to the individual starters and motors can be proceeded with almost as soon as the corresponding auxiliaries have been installed. The routes of the majority of these cables will have been selected before the foundations were cast and usually consist of trenches and cable pipes. An insulation test will be taken on each motor and its associated cables and starting equipment and some motors may require drying out before running. Many of the motors will have to be tried for direction with the drives un-coupled.

Main Switchgear. Having outlined generally the procedure with auxiliary supplies it is seen that everything centres round the main switchgear. Take, for example, a present-day case, the outside network may be operating at 132 kV. whilst the generation voltage at the new station is 33 kV. The transformers at the sub-station will therefore be arranged to have a ratio of 132 kV. to 33 kV. and be connected direct to the main station switchgear which will be at 33 kV. To obtain supplies for the auxiliary services and perhaps a few local feeders, further sub-division of voltage will be necessary.

Assuming 11 kV. local feeders are decided upon it will be necessary to provide 11 kV. switchgear, and if the highest voltage for auxiliary services be 6·6 kV. or 3 kV. further switchboards will be required. It will thus be seen that each switchboard in the chain

must be completely erected, preferably in every detail, and tested before supply to the lower voltage auxiliary services is available.

In a new station, many of the buildings will be newly built and the switchgear may have been erected before final drying-out of the buildings is possible. Local weather conditions may have further aggravated matters with the result that special heating will be necessary to bring the higher voltage gear up to standard.

An over-voltage test will be applied to each unit before it is put into service and this will necessitate close co-operation with the operating staff which, although just in its infancy, must be responsible for all plant made "alive." The operation of each circuit breaker should be checked on both local and remote control with normal and low battery volts. All protective relays associated with a unit should be tried for tripping and given a final check before handing over. If a master tripping relay be fitted, only that relay need be tried, the individual relays associated with it merely being checked to trip the master relay. The stability and operation of all feeder relays may be checked as far as possible by injection currents in the secondary circuits. Where Merz-Price protection is fitted it may be necessary to arrange for a turbo-alternator at one end af the circuit to be run on a separate set of bus-bars for short-circuit testing. Operation tests may be arranged by reversing one current transformer secondary. The stability of the protective equipment should be proved, and this is in fact of much more importance than obtaining a fine check of the operating fault current. An easy and quick test for relay operation is possible if very low plug settings are available. This is convenient on inverse time limit relays fitted to works' feeder circuits as a number of motors may be run on light load and the operation checked under actual conditions. By placing the plug in 25 per cent. position a quick and convenient check of the functioning of the relay is made.

Circulating Water System. The procedure to be adopted will depend largely on the system and perhaps local conditions. Take the case of a cooling tower station; it is desirable to have at least one circulating pump running as soon as the tower stacks are completed. The internal stack is made up of a considerable quantity of dry timber which is liable to catch fire and by pumping water over it the risk is minimised. In addition to a pump being ready, one condenser together with all pipework must also be complete. All piping underground is tested for tightness before covering-up.

With a riverside station the penstocks can be opened to the

screening chambers and the screens run for periods. Jet cleaning pumps, penstocks and valves can be thoroughly tried out. Care should be taken where the pumps and pipes are left in a primed condition, to guard against frost. Where the screens are in very exposed positions it is sometimes necessary to make provision to guard against icing up. One method of dealing with this is to take a pipe from the condensers and convey warmed circulating water into the river just above the intakes. In this way trouble with ice at the screens during times of hard frost is avoided. On a small river it is possible that the installation of a fairly large pumping plant will draw in large quantities of surrounding deposits. By keeping one pump running at frequent periods any loose deposits will be gradually cleared. In this way a good water intake will have been established by the time the main plant is ready for putting into service. As with cooling tower systems one condenser and all main inlet and outlet pipes and culverts must be ready before this can be attempted.

Condensers. After the turbo-alternator foundations have been completed condenser erection is proceeded with. The main body or sections forming the body, when welded steel-plate construction is adopted, is placed in position and jointed up. Tubing is then completed and the steam space side filled with water over the tubes. In this way any defective joints, tubes, ferrules or expansions in the tube plates are noted. The body joints are also noted for defects and leaks, any tightening up found necessary being done. The adjustments to the supporting springs have to be made to allow for future filling of the steam side. The condenser is then emptied. After this test the return and water box ends may be fitted and the water side of the condenser filled with water. The condenser will be loaded to about normal working conditions and any adjustments necessary are made to the springs. The jointing up to the exhaust flanges is then completed. To test for leaks on heaters, ejectors, extraction pumps, inter-connecting piping, etc., the condenser steam side and the items mentioned may be filled with water and all tried together. Care should be taken to see that the main circulating water pipes are not putting any undue strain on the condenser flanges.

Turbines. A number of the auxiliaries will be available for running at an early date providing the turbine is ready ; these being the auxiliary oil pumps and barring gear. The oil system is usually completed fairly early as many of the pipes have to be in position

before the surrounding floor can be finished. The oil tank, coolers, pumps and inter-connecting pipe-work should be thoroughly flushed with a light oil for some time. A number of oil suppliers provide a full charge of flushing oil for this purpose and recommend that it be continuously sent through the complete oil system for about a fortnight. One oil supplier recommended that the flushing oil should be in service for a period of 200 hours, whilst another suggests a period not exceeding forty-eight hours with the set on light load. The cleaning of a system on an hour basis may give varying results. From a practical point of view there does not appear to be any reason why a system should not be just as clean after forty-eight hours as after 480 hours. In fact, it is a decided advantage to rid the system of the dirt as soon as possible, in which case a twenty-four-hour run may suffice. On the other hand, it may be argued that any loose core sand, etc., has a chance to become dislodged after a prolonged run due to vibration and movement of the pipes, etc. If electrical barring gear is fitted the set can be kept turning and the flushing oil circulated through the system as conditions permit. This flushing oil is generally similar to the oil used for normal service except that it is lighter and more effective for cleaning.

The quantities of oil used for varying sizes of turbo-alternators have been given and the filling and withdrawal of this flushing oil from the system involves a certain amount of time. After the system has been emptied, the tank, strainers, coolers and all pockets where the lodgement of foreign matter is possible should be thoroughly cleaned before finally filling with the service oil. The oil system to the governor gear can also be checked and adjustments made.

The lagging of the steam chests, cylinders, cross-over pipes and auxiliary pipes has to proceed according to a pre-determined plan. The method adopted will depend primarily on the type of lagging to be used. If magnesia is used a supply of low pressure steam must be available and the whole of the parts to be so treated gradually heated to between 90° and 110° F. The use of glass silk obviates the necessity for steam warming-up and this form of heat insulation is becoming increasingly popular.

It is advisable to leave all joints unlagged until final vacuum or pressure tests have been applied otherwise small leaks will be difficult to locate. It has been suggested that all lagging should be completed and the set given a thorough clean down before charging the oil system. This has many advantages but much will

depend upon the contract generally and the need for the new set to be in commission as soon as possible. Attention should be paid to the condition of steam traps and tundishes, and frequent inspection of the former is desirable during the early stages. Once steam is available at the turbine stop valve it is possible to try the steam-driven auxiliary oil pump, also starting and main ejectors. The regulator for the turbine of this pump should be operated by the lever provided and adjustments made. If this regulator fails the by-pass valve can be opened in an emergency. Opinions differ as to where this regulator should be situated. The usual position is near the steam end of the set and preferably above the floor, providing the steam piping connected to it can be properly drained, and kept from the main walkways. It is rather unsightly if placed in direct line with a gauge board or the main access ways around the turbine. The unit can be suspended under the operating floor with a cover to give access to the by-pass valve or the adjusting lever. So long as it is not tucked away in an inaccessible position, any other situation would be suitable.

The ejectors can be tried on a normal operating run with the glands sealed and vacuum raised. The starting or booster ejector should raise the vacuum to a desired value within the specified time. If the vacuum with starting and main ejector in operation does not come up as anticipated, leaks in the feed and condenser system should be looked for, *e.g.*, joints, gauge glass fittings, flooding of air suction, atmospheric valve correctly water sealed and the vacuum gauge correct. Leaky joints will be disclosed by making a search with tapers.

Starting up of the turbine follows the normal routine except that a much longer interval of time is taken for each successive step. Manufacturers' procedure differ and the set may be run on and off for a week before coming up to normal speed for the first time. During these low speed runs the exhaust end of the turbine should not be allowed to become overheated, and shut down for cooling off has to be taken into consideration.

Alternators. As soon as the stator is delivered to site it is advisable to place two or three electric heaters in the alternator foundation block for in this way the drying-out period to be undertaken later will be considerably reduced. Drying out is done by running the alternator on short-circuit at about 60 to 70 per cent. of the normal speed, although some makers prefer to run at normal speed. The leads are shorted at the stator terminals. If the

leads are shorted at the circuit-breaker spouts it will be necessary to disconnect the power factor indicator or short-circuit the current transformer leads to prevent the indicator revolving during the drying-out period. The detailed procedure to be followed with exciters, ventilating system, temperature and insulation resistance measurements is supplied by the manufacturers and must be followed. After the start of the drying-out run the insulation resistance will fall rapidly owing to the rise in temperature, and may even go below one megohm, so that only a low voltage "Megger" (500 volts) should be used in the early stages. After the insulation resistance has fallen to its minimum and is then on the rise a 2,500-volt motor-driven "Megger" may be used. The procedure to be adopted and the desired insulation resistance will vary according to the voltage of the alternator, special care being necessary with 33,000 volt alternators. The insulation should be checked every two hours. It is not necessary to shut down the set or interrupt the current when checking the insulation resistance except when the stator is short-circuited through long leads, or lead-covered cables, which have a low insulation resistance. These should be disconnected before checking. The drying-out run should be continued until the insulation resistance is steady, at a constant temperature at not less than the value and for the period stated by the manufacturers. A curve is usually drawn showing the insulation resistance and temperature plotted against time. Fig. 534 shows a typical drying-out curve. The drying-out can be accelerated by increasing the temperature of the cooling air, *i.e.* running the fans with throttled water supply. An air temperature of about 60° C. leaving the coolers is usual and it is necessary to ensure that any moisture from the windings is removed. This can be done by opening the emergency air dampers occasionally or alternatively raising the covers on the stator. A noticeable feature of drying out is that the insulation resistance of the windings drops rapidly from the initial value to a minimum at about the time the temperature reaches a steady value. It then rises slowly, but at an increasing rate with time, and drying out is continued until the reading is at a steady, satisfactory level It may be possible to complete all checks on the electrical protective system at the start of or during the drying-out run. On the other hand, these may be made on completion of drying-out and while the short is still on the stator terminals. Single-phase fault operation tests can also be tried. If an over-voltage test is to be applied to the alternator this may be done

while the stator is still hot. The rotor insulation may also be checked after drying-out and while still hot. The insulation is of course proved at the works and the actual drying-out of a rotor may extend over some months of normal operating conditions.

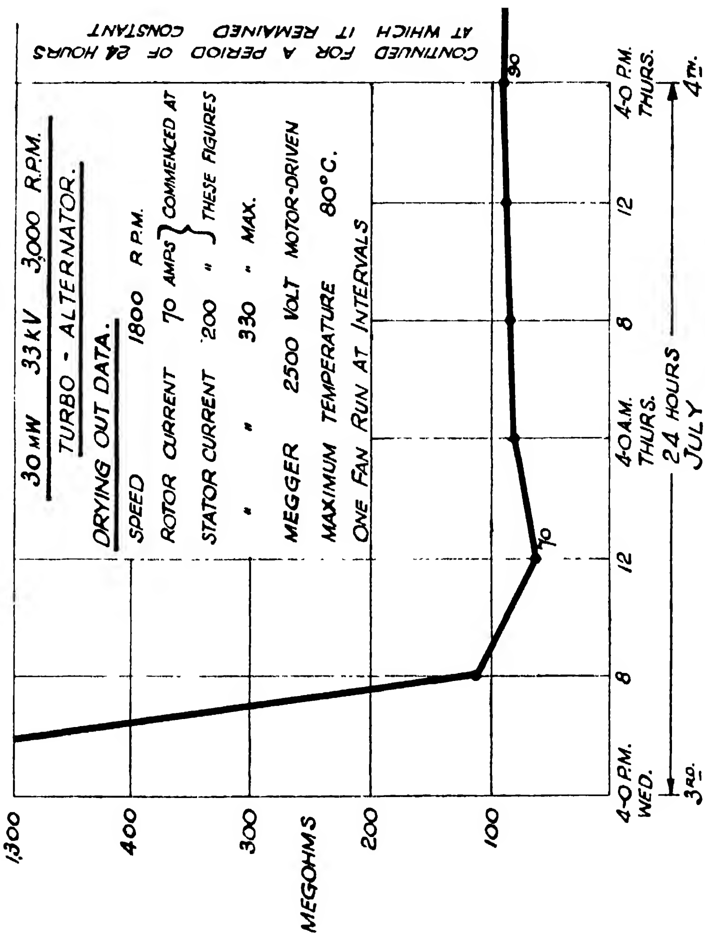

FIG. 534. Alternator Drying Out.

The rotor windings may, however, be pressure tested after drying-out if deemed necessary. Before placing the set on the bus-bars it is necessary to phase out and check the phase rotation. Voltage transformers will be required for this purpose and the connections will depend on the arrangement of the main switchgear. A phase-rotation indicator connected across the secondary terminals of the

voltage transformer will give the direction. This will have to be checked for both the existing and incoming supplies, and if the direction is the same in both cases the synchronising connections may be accepted as correct. The secondaries of the voltage transformers may be checked by voltmeter as follows :—Red to red—zero. Red to blue—full voltage. Red to white—full voltage, and so on.

In addition to these tests it is as well to check each to neutral. On inserting the synchronising plugs a twelve o'clock reading should be obtained on the synchroscope. It is usual to vary the speed of the incoming set up and down to ensure that when the synchroscope indicates "incoming fast" then the incoming set is fast. Some usual figures and tests are given :—

30 MW 33,000 VOLT 3,000 R.P.M. TURBO-ALTERNATOR

Date of test ....

Present..................................

Testing Equipment

25 kVA, 440/110,000 volts transformer with a spark gap (62·5 mm. diameter spheres). 37,500 volt tapping used. The spark gap was adjusted to jump at approximately 33,000 volts. A 2,500 volt motor-driven "Megger" was used.

Insulation Resistance Tests.	Before Application of Voltage	After Application of Voltage
	Megohms	Megohms
Red phase	2,100	2,100
Yellow ,, . . .	3,000	3,000
Blue ,, . . .	2,800	2,800

The "Megger" was run for ten minutes before noting I.R.

Voltage Tests

Red phase—30 kV.—B and Y phases earthed
Yellow ,, — ,, —B ,, R ,, ,,
Blue ,, — ,, —R ,, Y ,, ,,

This voltage was maintained for one minute in each case. The voltage was applied at both ends of each phase winding, the other two phases being shorted at both ends and earthed at one point. The rotor was shorted at the slip rings. The lower voltage single-

phase supply given during these tests was 400 volts, the current taken being 70 amps.

Temperatures

Turbine house	26° C.
Core	26° C.
End windings (exciter end) . . .	27° C.
,, ,, (turbine end) . .	25° C.

In some cases the rotor windings are pressure tested on site to 2,400 volts for one minute after drying-out.

Alternator Protective Apparatus, Phasing and Commissioning

Insulation Resistance Tests

Alternator and exciter windings to earth—in order.

Procedure

Previous to starting the sealing end phase terminal links were connected and the short-circuiting plugs inserted in main oil circuit-breaker cable spouts. Metering equipment current transformers were short-circuited. The turbine was then gradually run up to a speed of about 2,000 r.p.m. with field suppression and main exciter field switches closed. The field rheostat was then adjusted.

Overcurrent Protection (Stand-by)

A plug setting of 50 per cent. was made on three-pole P.B. overcurrent relay and the stator current gradually increased until all three poles operated.

Merz-Price Circulating Current Protection

The stator current was gradually raised to full load for relay stability test and this was found in order. The stability of the alternator at overcurrent rating can also be noted. The relays were tried for balance by testing the milli-volts drop across each relay at load currents of 100, 200, 400, 600 and 800 amps. A low-resistance milliammeter was connected in series with the relay coil (preferably in place of the relay coil) for each phase, *i.e.*, Top (R), Middle (Y), Bottom (B), and the out-of-balance current noted. If the current transformers are correctly balanced and the tapping points of the relay are correct, the out-of-balance at full load is usually never more than 12 milliamps. Readings of 1 to 10 milliamps are usual. It is advisable to provide a milliammeter of low impedance for this

test, otherwise the accuracy of the readings will be affected. The out-of-balance tripping effect was tested by creating an artificial out-of-balance in the relay circuit. The top pole current transformer was short-circuited and the stator current gradually raised and its relay operated satisfactorily. The set was then shut down; plugs were removed from main circuit breaker and a short-circuiting bar was placed on all three phases at the sealing ends. The set was then run up to about 3,000 r.p.m. and the stator current adjusted to about 70 amps. and all three poles of Merz-Price relay operated. The set was then shut down and 3-phase short removed.

Earth Leakage Protection (Stand-by)

Centre short-circuiting plug (ammeter in this phase) was inserted in main circuit-breaker spout and earthed. The liquid earthing resistor was short-circuited and neutral isolator and neutral circuit-breaker closed. The single-pole P.B. earth leakage relay plug setting was 10 per cent., and with a stator current of approximately 70 amps. the relay operated. The set was shut down and connections made normal. It is probably better practice to test either by injection to primary of current transformer or alternatively energise the relay coil. When earthing one phase of an alternator for test purposes it is possible to damage the winding insulation.

Phase Rotation of Alternator

The voltage transformer for the set was racked into position. D.C. tripping and closing fuses were inserted. Neutral circuit-breaker was closed and the set run up to full speed and excited to 33,000 volts. Phase sequence rotation indicator was connected across secondary terminals Nos. 21, 22 and 23 (110 volts) in the alternator control panel, and rotation was in direction of arrow, *i.e.*, R.Y.B.R. The voltage transformer voltages and polarities checked and all found in order. (V.T. tested phase to earth on secondary side and balance found correct.) The synchroscope responded to the governors with the 'Incoming' plug in for the new alternator and the 'Running' plug in for a set on the bus-bars. The set was then shut down.

Phase Rotation of 33 kV. Bus-bars

The sealing end links were removed. Before closing the alternator circuit-breaker on to the bus-bars the whole of the tripping circuits were tested.

Alternator circuit-breaker was closed when racked out.
Neutral circuit-breaker was closed.
Field suppression switch was closed.

The tripping was as follows :—

Overcurrent relay	operated	—	alterator	circuit-breaker	opened.	
Earth leakage relay	,,	—	,,	,,	,,	,,
Merz-Price ,,	,,	—	,,	,,	,,	,,
			neutral	,,	,,	,,
			field suppression switch			,,

Field suppression switch —alternator circuit-breaker opened.
(inadvertent operation)

The phase rotation indicator remained as connected with the alternator in circuit. The alternator circuit-breaker was then closed on to the bus-bars and the phase rotation was in direction of arrow (as before). The synchroscope was put into circuit and a twelve o'clock reading obtained. The voltage transformer voltages and balance were as before.

Voltage Regulator, Field Forcing and Metering Equipment

The set was run up to about 2,000 r.p.m. and the voltage regulator and field forcing equipment were tested. To check the operation of the field forcing equipment the exciter was disconnected at the terminal box and a separate 110-volt A.C. supply used to energise the motive system of the regulator. The exciter was excited to various voltages and fault conditions reproduced by suddenly lowering the value of the 110-volt supply. The regulator was adjusted for hand and automatic control after the set had been put on the bars. The set was then run to full speed and the alternator circuit-breaker closed on to a spare bus-bar (neutral circuit-breaker closed). A 10,000 kVA. transformer was isolated from the system and put on this bus-bar and the new alternator was synchronised on the 6·6 kV. bus-bar. A load of 5,000 kW. was maintained for a short time to enable the metering equipment to be checked. The overcurrent and earth leakage relay settings were the lowest obtainable.

Final Commissioning

Overcurrent relay setting (800/5 C.T.) 100 per cent.—0·5 time multiplier.

Earth leakage relay setting (400/5 C.T.) 20 per cent.—1·0 time multiplier.
Merz-Price relay has fixed setting of 0·2 amp.

Sustained fault current with voltage regulator is about 1,300 amps. (900 without V.R.). Set run up to speed and synchronised with 33 kV. system and load gradually raised to 8,000 kW.

To provide overcurrent protection for the alternator it is necessary that the setting is sufficiently low to cause tripping with sustained fault current of the alternator. The neutral of the set is always earthed when bringing it on to the bus-bars. After that it can be opened and run insulated providing another earth exists.

Transformers. If delivered to site full of oil they may be connected and put into service as conditions permit. Should the oil be sent separately, then, after filling, drying out will be necessary. This is carried out in a similar manner to that for alternators. On step-up transformers the auxiliaries, such as fans, pumps, etc., will have to be tried out. When applying line voltage for the first time it is better if the voltage can be increased gradually and the transformer allowed to remain on open circuit "soaking" for some time.

Boilers. The procedure to be adopted will depend on the make and the type of boilers installed. On completion of expanding the tubes and the approval of the Insurance Company having been obtained, the boiler may be filled ready for hydraulic testing. Any clean water such as that taken from river or well is usually quite suitable for this purpose. In the meantime certain portions of the brickwork may be proceeded with, but all headers, joints, etc., should be left uncovered to facilitate inspection. Care must be taken to guard against frost, and it is possible that considerable delay may be caused by this. The methods of cleaning by boiling vary, but the underlying principle is the same, and that is to remove all traces of sludge, oil and other foreign matter. During the boiling period, which may be anything up to a week, the drains are only blown down enough to create sufficient flow to heat up the water wall tubes, etc. After this process has been completed the boiler is emptied *viâ* the mud drums and at the same time the other drums are opened as found necessary. The boiler is then opened up for a thorough cleaning, after which a protective coating may be applied to the interiors of the drums and tubes, also the internal fittings. The coating is sometimes applied to the tubes before

erection. In some cases the tubes are left untreated. On completion of this work and final examination of all the pressure parts, the process of filling up with condensate and raising the pressure may commence. The raising of the pressure is rather slow and may take up to six days to attain full working pressure and set the safety valves. In setting safety valves a minimum margin above the working pressure is required for the valve set at the lowest pressure and the settings are usually staggered. The superheater valves should open before the first drum valve and be the last valves to close. After a new boiler has been in service for a month or so it is usual to open out for cleaning as considerable deposits are frequently found on the feed trays and in other pockets. The lagging and general heat insulation follow the lines mentioned under turbines.

When stoker-fired boilers are used the stoker drives must be tried out and also ash crushers if the retort type is adopted. With pulverised fuel boilers the milling plant, burners, electrostatic precipitation plant and other items will have to be tried out and adjustments made. Draught fans, air heaters, valve controls and other auxiliaries will be given a series of runs before final commissioning. A typical set of test reports relating to boiler inspection and construction are included.

NO. 1 PULVERISED FUEL BOILER—130,000 LB. PER HOUR —300 LB. 750° F.

Summary of Principal Tests before Commissioning

Dry Test

Insurance inspector examined boiler in course of construction noting expansion of each tube. Ball passed down tubes. Drums, side walls and generating tubes examined and all found in order.

Hydraulic Tests

Boiler and superheater were subjected to a test pressure of 580 lb. p.s.i., this being maintained for one hour and twenty minutes. All in order.

Economiser subjected to a test pressure of 550 lb. p.s.i. and maintained for thirty minutes. All in order.

Drying Out and Feed Water Filling

(1) Fires were placed in combustion chamber and brickwork gradually dried out.

(2) Sufficient river water was admitted to boiler to give adequate head on headers and drains.

(3) All blow-downs and drains were opened and boiler emptied.

(4) All blow-downs and drains were subsequently removed for inspection purposes.

(5) Boiler filled up to a working level with water (softened, town main or river, depending on local conditions), a charge of soda-ash being included.

(6) Lighting-up and boiling were proceeded with after which boiler was completely drained.

One mill was run and boiler brought up to boiling with the aid of paraffin torch in one burner. Oil lighting-up burner not available.

(7) Boiler filled to normal working level and with one mill on, pressure was gradually raised to 70 lb. and held at this figure for about two hours.

Floating of Safety Valves

The valve maker's representative attended for "floating" operations.

No.	Valve.	Set Pressure (lb p.s.i.)	Lift Pressure (lb. p.s.i.)	Shut Down Pressure (lb. p.s.i.)
1	L.H. rear drum	350	353	342
2	R.H. ,, ,,	350	353	344
3	L.H. steam receiver drum	345	346	338
4	R.H. ,, ,, ,,	340	343	330
5	Superheater	315	318	312

In some cases the superheater safety valve is given a slightly higher setting to prevent excessive blowing off.

Instrument Settings

The instrument makers' representative attended to carry out the necessary adjustments to the draught gauges, meters, etc.

Blowing Through and Putting on Range

The air-release valves were opened to rid the range of any air.

The main steam receiver was shut down and isolated, the traps being by-passed.

No. 1 boiler was brought up to approaching working pressure. Boiler isolating valve was then opened and steam passed to receiver. After some time the boiler and receiver were again isolated and the manhole door on the latter removed for internal inspection. Very little scale was present and no solids found. Boiler brought up to working pressure, put on range and loaded to about 80,000 lb. per hour.

On starting up pulverised fuel boilers it is important to cut down oil burning to a minimum as partially burnt oil tended to deposit on the boiler surfaces. To prevent overheating, thermocouples can be fitted to the superheaters and these will show the need for intermittent firing when bringing a boiler up to pressure and temperature so avoiding overheating.

Boiling-out Procedure. This appears to vary and the following has been adopted for 600 p.s.i. ; 800° F. plant. Boiling out done in two stages :—

(1) Soda-ash in water at atmospheric pressure for 24 hours, the proportions being 250 lb. per 1,000 gallons of water. The oil emulsion formed on the surface of the water in the drum is skimmed off through the manhole before blowing down.

(2) After blowing down the boiler is filled again, charged with tri-sodium phosphate in the proportion 250 lb. per 1,000 gallons of water, together with 4½ lb. per 1,000 gallons of sodium aluminate, and boiled for 24 hours at a pressure of about 200 p.s.i. Sodium aluminate forms an aluminate flock with the decomposed particles of oil causing a precipitate which can be removed from the mud boxes. When the boilers are washed out there is no sign of grease and the surfaces are generally in good condition.

Feed Water System. In outlining the turbine and boiler plant procedure no mention was made of the feed system or the feed water. The feed system varies in detail for almost every station but similar items of plant are always present—low and high pressure feed heaters, feed pumps, evaporators, surge and storage tanks. All except the tanks call for little comment as the taking over tests can only be carried out when the plant is in commission. The tanks are usually filled with water to test for leaks and try out the level transmitters and indicators. The lagging and heat insulation is similar to that carried out on the turbines. Before a start can be made on commissioning the boilers and consequently the turbo-alternators, it is necessary to have a large quantity of feed water.

How this is obtained will depend on local conditions, if, however, the new plant is an extension to existing plant there is no need for anxiety. Two methods which have been adopted are: transporting water from an existing station; installing temporary donkey boilers and condensers for evaporating town main water. Having obtained the necessary amount of feed water and filled the surge and storage tanks, the problem now to face is that of getting it into the boilers. An iron-exchange water softening plant can be installed to prevent delay in obtaining make-up water on a new site. Assuming extensions, then the existing feed pumps could be used for filling, the feed-water being drawn from existing hot wells, sufficient additional make-up having been stored in the new tanks. The feed control valves would require throttling during the filling process.

In fairly old plant the feed-water would probably be at a temperature of 100° to 160° F., and even then overloading of motor-driven pumps would be possible if worked down to abnormally low ratings. It should be remembered that the boiler pressure at the early stages may not exceed more than 50 to 100 lb. per square inch, and this may be maintained for some weeks during lagging and making good any defects. If a steam turbine-driven pump exists it may be operated on the throttle instead of the governor and in this way it is possible to follow the steam pressure right from the lowest to the highest pressures, *i.e.*, normal boiler pressure. If it is an entirely new station a steam turbine-driven pump could be installed which would take its supply direct from a reserve feed storage tank. It would be operated as mentioned and arranged to exhaust direct to atmosphere. The question of steam supply is still present. The alternative is to provide a small motor-driven feed pump to serve until the turbine-driven pump can take over at a reasonable pressure. This motor-driven pump could take its supply from the station battery so as to make it independent of station auxiliaries, particularly in the early stages. The feed system should be thoroughly examined during the commissioning period and all air release and drain valves operated at frequent intervals. After emptying a feed range or leg completely it is always advisable to rid it of air before putting it on to steaming boilers otherwise large quantities of air will be fed into the boilers with the feed water. This air will eventually find its way into the turbines and may impair the vacuum to such an extent as to put a set out of commission should it be operating under poor vacuum conditions. Provision of adequate air release valves is essential at the highest points on

all ranges and legs or risers. Where two feed ranges are provided arrangements can be made to recharge an empty leg by either a feed pump or reserve leg, the air-release valves on the reserve range being used to clear the air from the system. The main valve by-pass connections can be arranged to take an air-release valve.

Coal and Ash Plants. The individual items of plant will be tried out under varying load conditions and all sequence operations checked.

Weather conditions may have considerable effect on the functioning of certain sections, such as conveying plant, etc.

TESTING OF PLANT

It is not proposed to delve into detailed tests of power-station plant, but merely to give a few of the leading formulæ associated with some of the usual tests and also typical test figures for some items of plant.

Turbines. The usual tests are as follows :—

(1) Efficiency Ratio. The turbine is tested under load and the actual steam consumption found. Let this be ω lb. per kW. hour. From measurements taken of the steam pressure and temperature the heat drop may be estimated. Let H be the adiabatic heat drop in B.Th.U. per lb. of steam and E_R the efficiency ratio of the turbo-alternator plant or overall efficiency.

Then
$$E_R = \frac{3{,}412}{H \times \omega}$$

The efficiency ratio is also $= \dfrac{\text{theoretical steam consumption}}{\text{actual steam consumption}}$.

The efficiency ratio of the turbine alone may be found if the alternator efficiency is obtained from separate tests at corresponding loads.

If E_a be the alternator efficiency

Then
$$E_{RT} = \frac{3{,}412}{H \times \omega \times E_a}$$

The following data would be required :—

Total temperature	= ° F.
Gauge pressure	= lb. p.s.i.
Vacuum at turbine exhaust flange	= in. Hg.

Theoretical adiabatic heat drop from initial steam conditions to vacuum $= (H_1 - H_3)$ B.Th.U.'s per lb.

Efficiency of alternator $= E_a$ per cent.

Thermo-dynamic efficiency of turbine $= E_{RT}$ per cent. (or efficiency ratio).

Overall efficiency of turbo-alternator $E_R = \dfrac{E_a \times E_{RT}}{100}$ per cent.

Normal steam consumption of set when no steam is bled for feed heating $= \dfrac{3{,}412 \times 100}{(H_1 - H_3) \times E_R}$ lb. per kW. hour.

(2) Thermal Efficiency. Let kW. be the output of the alternator.

$$\text{Power at turbine coupling} = \frac{\text{kW.}}{E_a}$$

Heat equivalent of power at coupling $= \dfrac{3{,}412 \times \text{kW.}}{E_a}$ B.Th.U.'s per hour.

Heat supplied to turbine per hour $= W\ (H_1 - H_4)$.

Where W = steam consumption lb. per hour.

H_1 = heat content of the steam at stop valve.

H_4 = heat content of water at exhaust temperature.

$$\text{Thermal efficiency} = \frac{3{,}412 \times \text{kW.}}{E_a \times W\ (H_1 - H_4)}.$$

The heat consumption figures may be calculated as follows :—

Heat consumption per kW. hour $= (H_1 + 32 - t)\ \omega$.

where t = final feed temperature ° F.

ω = lb. per kW. hour including feed heating steam, but excluding all condenser auxiliaries (steam and power).

The correction curves submitted by the contractor for steam pressure, steam temperature, vacuum, inlet feed water temperature and power factor are utilised to correct the observed results obtained.

The test readings may be grouped as follows :—

(1) Turbine readings to determine heat drop.
(2) Water measurements to determine consumption.
(3) Electrical readings to determine load.

The turbine readings are as follows :—

(1) Pressure at stop valve.
(2) Pressure after governor valve (designer's use only).
(3) Temperature before stop-valve.
(4) Vacuum.

The steam pressure gauges should be calibrated for accuracy against a deadweight tester. Due allowance should be made for

the head of water in connecting pipes if the gauge centre lines are either above or below the point of connection. Instruments on the turbine gauge board will have been graduated to suit such conditions. The pressure after the governor valve indicates the amount of throttling through the valve and true adiabatic heat drop through the turbine blading.

The steam temperature should also be measured after the governor valve. All important thermometers should be checked against a standard before tests.

Pressures and temperatures may be taken at various stages of the turbine for the determination of the condition-line.

Steam Consumption. The steam used may be tabulated as follows :—

(1) Steam used by blading.
(2) ,, ,, glands.
(3) ,, ,, ejectors.
(4) ,, ,, auxiliary oil pump (during starting up and shutting down).

In a steam consumption test it is necessary to pass the above quantities to the main condenser and weigh the whole amount together. The steam to the auxiliary oil-pump turbine and starting ejector is usually exhausted direct to atmosphere.

The only exact method of measuring condensed water for steam consumption tests is weighing of the water or measuring it in calibrated tanks.

The usual method of weighing the condensate is to place a large tank on a weighing machine. The tank is open at the top and has large drain pipes in the bottom fitted with quick-acting sluice valves. A tank of larger capacity is placed above the weigh tank and is also fitted with drain sluice valves (Fig. 535). The larger tank commonly referred to as the storage tank receives the condensate and then passes it on to the weigh tank, where it is weighed at regular intervals. An alternative method suitable when no weigh bridge is available is to place two calibrated volume tanks fitted with gauge glasses in the basement. The quantity of steam used is then derived from the volume of water discharged.

Correction Factors. It is not always possible to maintain the steaming conditions constant at the designed figures for long periods, and it is therefore necessary to introduce correction factors. The manufacturer will supply curves giving separate correction factors for variation of steam pressure, variation of superheat, and variation

of exhaust pressure. Any change in heat drop will affect the efficiency of the turbine. The change caused by variation of pressure or superheat is usually insufficient to affect seriously the internal efficiency, but a change of vacuum causes considerable disturbance of the distribution in the final stages, and also a large variation of leaving and exhaust losses.

Driving of Set. Correct conditions should always be obtained before proceeding with tests. The vacuum should be adjusted to its correct value. The load also should be set correctly, the main governor valve not being unduly throttled. By regulating the

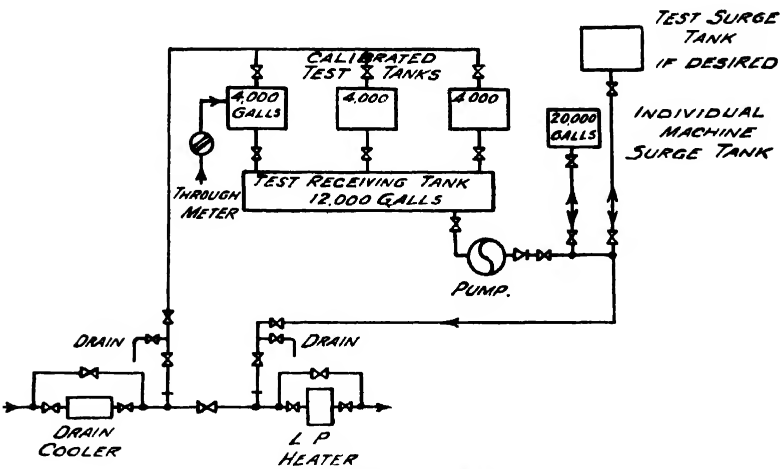

FIG. 535. Typical Test Tank Layout.

water flow through the oil coolers the bearing temperatures may be adjusted. A steady stop valve temperature is also essential. A heat loss is incurred when the temperature rises due to the warming of the turbine cylinder, rotor, etc. The turbine materials give up heat to the steam when a temperature drop occurs, but as it absorbs heat with a corresponding temperature rise, although not to the same extent, loss of efficiency is incurred by these fluctuations. Change in load calls for variation of initial pressure and the load should be kept constant as this in turn is usually accompanied by temperature change, and a loss occurs in the same way as that produced by change of stop-valve temperature. The condenser should be thoroughly clean on the waterside and be free from leaks. A leaky condenser when under vacuum will allow cooling water to

leak into the steam space and results in incorrect condensate readings being recorded. If a Di-onic water recorder is fitted, any appreciable increase from normal conditions will be noted. Alternatively, samples of condensate and cooling water may be taken in clean glass bottles. The electrical conductivity of these samples is then determined by a Di-onic tester and compared with the conductivity of pure water. If the conductivity of the condensate is appreciably greater than that of the pure water a leakage of cooling water into the condensate should be suspected.

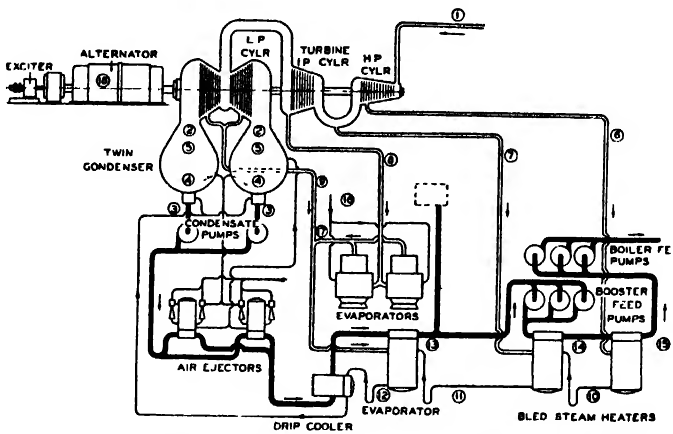

FIG. 536. Turbo-Alternator Plant Points of Temperature Measurement.

(1) Superheated steam.
(2) Exhaust steam.
(3) Turbine condensate.
(4) Circulating water inlet.
(5) ,, ,, outlet.
(6) to (9). Bled steam from turbine.
(10) to (12). Evaporator and feed heater drains.
(13) to (15) Condensate at feed heater outlets.
(16) Raw water inlet to evaporators.
(17) Vapour outlet—evaporators.
(18) Alternator temperatures, stator windings, cooling air, water to air and oil coolers, bearing oil, etc.

Fig. 536 indicates points of measurement.

Alternators. The electrical output is one of the most important measurements and therefore demands the use of high-grade test instruments. This may involve the installation of test-current transformers and voltage transformers together with accurate standard test instruments.

Boilers. The testing of boiler plant is fairly well known and it is only necessary to include some principal items.

Gross Thermal Efficiency, or the ratio that the heat put into the feed water in converting it into steam bears to the available heat in the fuel as fired.

$$\text{Gross Thermal Efficiency} = \frac{W(H_1 - h)}{W_c \times C_v} \times 100 \text{ per cent.}$$

Net Thermal Efficiency, or the ratio that the heat put into the feed water in converting it into steam less the equivalent heat value of the power required for the auxiliaries (fans, stoker motors, etc.) bears to the available heat in the fuel as fired.

$$\text{Net Thermal Efficiency} = \frac{W(H_1 - h) - U \times HE}{W_c \times C_v} \times 100 \text{ per cent.}$$

W = Total weight of water evaporated in a given time in lb.
H_1 = Total heat of steam (from Steam Tables) corresponding to the pressure and temperature of the steam at the boiler or superheater outlet in B.Th.U.'s per lb.
h = Sensible heat of the feed water (from Steam Tables) $(t - 32)$.
W_c = Total weight of coal burned in the given time corresponding to that for the water weight in lb.
C_v = Gross calorific value of the fuel as fired in B.Th.U.'s per lb.
U = Total power absorbed by the boiler auxiliaries such as fans, milling plant, stokers, etc., during the given test time, in kW. hours.
HE = Heat equivalent of the auxiliary power in B.Th.U.'s per kW. hour.

The heat equivalent of the auxiliary power to be used—HE—should be specified in the original tender upon which the order is placed, but if no such figure is available the value should be calculated from the expression.

$$HE = \frac{3{,}412 \times 100}{TE_o}.$$

TE_o = Average overall thermal efficiency of the station at the time of the tests in per cent.
T_H = Total heat consumption of turbine including all auxiliaries B.Th.U.'s.
kW. (N.E.R.) = Normal external load of turbo-alternator.

Heat consumed by turbine house plant per kW. hour of normal external load $T = \dfrac{T_H}{\text{kW. (N.E.R.)}}$ B.Th.U.'s per kW. hour.

Overall efficiency of turbine house plant,

$$TE_o = \frac{3{,}412 \times 100}{T} \text{ per cent.}$$

The net boiler efficiency is really a more practical figure, since it shows the true net output obtained from the fuel after taking into account the power absorbed by the auxiliaries necessary to effect the conversion and makes the comparison of different types of firing or water circulation more significant.

Equivalent Evaporation. The equivalent evaporation per lb. of coal from and at 212° F. is given by :

$$E_E = \frac{W \times (H_1 + 32 - t)}{L} = W \times f_e$$

where W = lb. of water actually evaporated per lb. of coal.
H_1 = total heat in B.Th.U.'s per lb. of steam at the boiler working pressure from 32° F. (from Steam Tables)
t = temperature of feed water °F.
L = latent heat per lb. of steam (970·7).

The evaporation from any given feed water temperature can be corrected to the datum line of 212° F. from the above.

The factor of evaporation may be estimated as follows :

$$f_e = \frac{C_v.E.}{W.L.} = \frac{(H_1 - h)}{L}$$

Where E = the boiler efficiency.
C_v = calorific value of coal in B.Th.U.'s per lb.

Heat Balance. Consists of estimating the various calculable losses which include :

Heat lost in dry flue gases.
,, ,, ,, evaporating moisture in fuel.
,, ,, ,, ,, ,, due to hydrogen in fuel.
,, ,, due to incomplete combustion of carbon.
,, ,, ,, ,, combustible matter in ash.
Radiation and unaccounted losses.

The test readings include :

Steam pressure, steam temperature, feed temperature, final gas temperature, air temperature and CO_2.

The measurements include : Weight of coal fired and weight of water evaporated.

Points of measurement are shown on Fig. 537.

The approximate heat-balance calculations are :

(1) Heat absorbed by water during its transfer into steam

$$= W(H_1 - h) \text{ B.Th.U.'s.}$$

This may be subdivided into

(a) Heat transferred in economiser.

(b) ,, ,, ,, boiler.

(c) ,, ,, ,, superheater.

$$h = (t - 32) \text{ approx.}$$

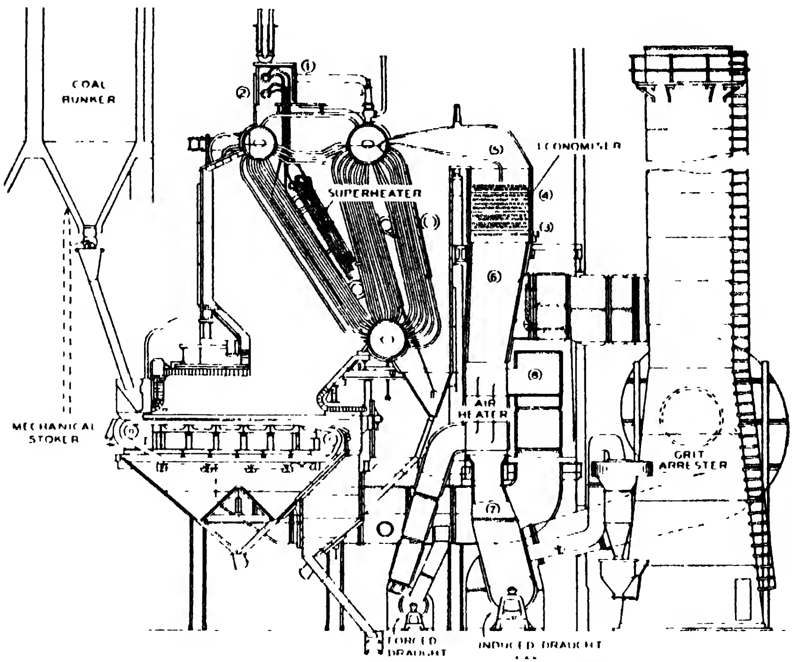

FIG. 537. Boiler Plant Points of Temperature Measurement

(1) Saturated steam.
(2) Superheated steam.
(3) Feedwater at economiser inlet.
(4) ,, ,, ,, outlet.
(5) Flue gas ,, inlet.
(6) ,, ,, outlet.
(7) ,, ,, air heater outlet.
(8) Air (hot air to grates).

(2) Loss of heat in dry flue gases

$$= W_g(T_g - T_a)\, 0{\cdot}24 \text{ B.Th.U.'s.}$$

T_g and T_a are the temperatures of the exit gas and inlet air respectively, and W_g is the weight of dry flue gases.

(3) Loss due to water obtained from the combustion of the hydrogen in the coal

$$= 9H\,[(212 - T_a) + 970{\cdot}7 + 0{\cdot}48\,(T_g - 212)] \text{ B.Th.U.'s approx.}$$

(4) Loss due to moisture in coal

$= M[(212 - T_a) + 970{\cdot}7 + 0{\cdot}48\,(T_g - 212)]$ B.Th.U.'s approx.

Where M is the weight of moisture per lb. of coal.

$$M = \frac{21(CO_2 - CO)}{21 - O_2 + 0{\cdot}395\,CO}.$$

Knowing M enables the theoretical weight of moisture in the gases per lb. of combustible to be ascertained thereby providing a check on the presence of steam in the flue gases. (See *Engineering*, Vol. 157, page 375, 1944). It is applicable whether there is any CO present or not.

(5) Loss due to incomplete combustion in carbon (*i.e.*, loss due to CO formation)

$$= \frac{CO_g}{CO_g + CO_{2g}} \times C \times 10{,}140 \text{ B.Th.U.'s approx.}$$

10,140 = difference in heat value of 1 lb. of coal burned to CO_2 and CO respectively = (14,540 − 4,400).

(6) Loss due to combustible matter in ash

$$= A \times C_a \times 14{,}540 \text{ B.Th.U.'s.}$$

Where A is the weight of ash per lb. of coal as fired and C_a is the weight of carbon per lb. of furnace ash or clinker. Alternatively, if the actual weight of ash, including the unburnt ash is not available, the loss in efficiency, due to the unburnt carbon in clinker can be estimated as follows :

$$\% \text{ Loss in efficiency} = \frac{A \times U_c \times 14{,}500}{(100 - U_c)\,CV}.$$

A − percentage of ash as determined by fuel analysis.
U_c − ,, ,, unburnt carbon or combustible in clinker.
CV − calorific value of fuel in B.Th.U.'s/lb.

E.g., A − 15 per cent., U_c − 25 per cent., CV − 10,500.

$$\% \text{ Loss} = \frac{15 \times 25 \times 14{,}540}{(100 - 25) \times 10{,}500}$$

$$= 6{\cdot}95 \text{ approx.}$$

(7) Loss due to riddlings or grit

$$= W_r \times CV_r$$

where W_r is the weight of riddlings and grit per lb. of coal and CV_r is the calorific value of these.

(8) Radiation and unaccounted losses.

By difference = CV − sum of items 1 to 7.

Fig. 538 shows boiler efficiency curve.

Fuel Testing. The calorific value of the fuel is determined by a bomb calorimeter. The ultimate coal analysis made by the chemist gives the following :—

C -- Weight of carbon per lb. of coal.
H — ,, ,, hydrogen ,, ,,
O — ,, ,, oxygen ,, ,,
S — ,, ,, sulphur ,, ,,

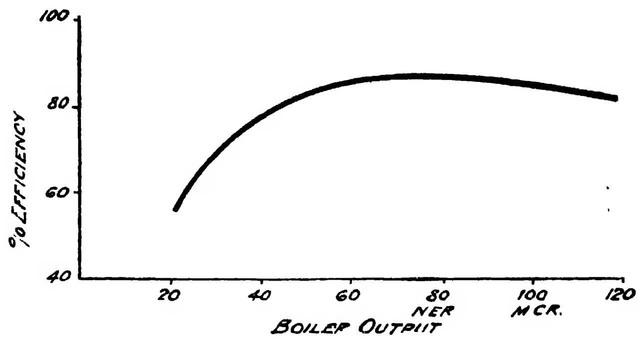

FIG. 538. Typical Boiler Efficiency Characteristic.

The equations representing the combustion, together with the combining weights of the reactants, are as follows :

C	+	O_2	=	CO_2 (carbon dioxide)
12 lb.		32 lb.		44 lb.
H_2	+	O_2	=	H_2O (water)
2 lb.		16 lb.		18 lb.
S	+	O_2	=	SO_2 (sulphur dioxide)
32 lb.		32 lb.		64 lb.

Air contains 23·2 per cent. oxygen and the remainder may be considered to be nitrogen. The weight of air required by each of the combustibles is calculated as follows :

$$\text{1 lb. of carbon requires } \frac{32}{12} \cdot \frac{100}{23{\cdot}2} = 11{\cdot}5 \text{ lb. of air}$$

$$\text{,, hydrogen ,, } \frac{32}{4} \cdot \frac{100}{23{\cdot}2} = 34{\cdot}5 \quad \text{,,}$$

$$\text{,, sulphur ,, } \frac{32}{32} \cdot \frac{100}{23{\cdot}2} = 4{\cdot}3' \quad \text{,,}$$

Weight of air (theoretical) for combustion, W_a

$$= 11{\cdot}5\ C + 34{\cdot}5\ H - 4{\cdot}3\ (O - S)$$

where W_a is the lb. of air required per lb. of coal.

The volume of air (theoretical) $V_a = W_a \times 12{\cdot}39$.

The theoretical air formulæ may be expressed as

$$W_a = 34{\cdot}5\left[\frac{C}{3} + \left(H - \frac{O}{8}\right) + \frac{S}{8}\right]$$

Actual air required per lb. of dry coal $= \dfrac{N}{33\ (CO_2 + CO)}\ .\ C$ lb.

Heat lost in excess air = excess air . $0{\cdot}24\ (T_g - T_a)$ B.Th.U.'s.

The theoretical evaporative power of a fuel is given as the weight of water evaporated from and at 212° F. per lb., or

$$\frac{\text{Gross calorific value of fuel}}{\text{Latent heat of steam at 212° F.}}$$

e.g., CV = 12,000 B.Th.U.'s per lb. L = 970·7 B.Th.U.'s

then water per lb. of fuel $= \dfrac{12{,}000}{970{\cdot}7} = 12{\cdot}6$.

The calorific values of the constituents in a fuel are approximately as follows:

Carbon to CO_2	14,540 B.Th.U.'s per lb.
,, ,, CO	4,400 ,, ,,
Hydrogen to H_2O . . .	62,000 ,, ,,
Sulphur to SO_2	4,150 ,, ,,

From the ultimate analysis the calorific value can be estimated from:

$$\text{CV (B.Th.U. per lb. of fuel)} = 14{,}540 + 62{,}000\left(H - \frac{O}{8}\right) + 4{,}150\ S.$$

The theoretical temperature rise of combustion may be estimated from the calorific value of the coal. Assuming the calorific value to be 12,000 B.Th.U. per lb. and the theoretical air required for combustion 13 lb. the total gas is therefore 14 lb. (specific heat, say, 0·267), then theoretical temperature rise in furance is

$$\frac{12{,}000}{14\ .\ 0{\cdot}267} = 3{,}200^\circ\ \text{F. approx.}$$

To this should be added the inlet air temperature to the stoker windbox or secondary air to the burners of pulverised fuel. The furnace temperature so estimated does not take into account the

moisture-content deduction and the allowances for the heat-absorbing surfaces. The latter include water walls, so that the amount of heat absorbed by radiation is proportionately the difference of the absolute temperatures of the furnace itself and the heat-absorbing surfaces. The admission of excess air to a boiler furnace will raise instead of lower the temperature of the flue gases.

Flue Gas Analysis. The apparatus used for routine testing of flue gas is the Orsat unit (Fig. 539), and the gases estimated are carbon dioxide (CO_2); oxygen (O_2); and carbon monoxide (CO).

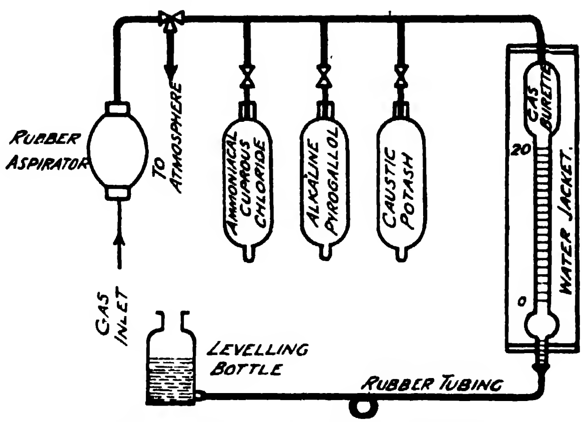

FIG. 539. Orsat Gas Analysis Apparatus.

The gases are absorbed in the following order by the reagents given:

(1) CO_2 by potassium hydrate solution.
(2) O_2 ,, alkaline pyrogallate solution.
(3) CO ,, prepared cuprous chloride in acid solution.
(4) N ,, difference, *i.e.*, 100 per cent.—(CO_2% + O_2% + CO%).

The apparatus consists of a water-jacketed gas burette connected by a common line of coarse capillary tube and tapped connections to three absorption pipettes containing these solutions. A levelling-tube is connected to the base of the gas burette to enable readings to be taken at constant pressure and for use in transferring gas to and from the absorption pipettes.

Typical flue gas formulæ computations are given:

Volume of dry flue gases per lb. of fuel, $V_g = V_{gt}\left(\frac{CO_{2t}}{CO_{2g}}\right)$ ft.^{3}

where V_{gt} = Volume using theoretical air

$= 29{\cdot}85\ C + 12{\cdot}8\ (0{\cdot}77W_a + N)$ ft.³ at N.T.P. approx.

t — refers to theoretical air

g — ,, ,, actual gas conditions.

Weight of dry flue gases per lb. of fuel

$$W_g = C\left[\frac{(11CO_2 + 8O + 7(CO + N)}{3\,(CO_2 + CO)}\right] \text{lb.}$$

Effect of Feedwater Temperature on Superheater Temperature. Assume normal operating conditions—130,000 lb./hr. evaporation 450 p.s.i. abs., 756·5° F.; saturation temp., 456·5° F.; 320° F. inlet feedwater, 400° F. economiser outlet.

Heat input $= H_1 - h$

$= 1{,}390 - (320 - 32)$ H_1 — total heat in steam leaving superheater.

$= 1{,}102$ B.Th.U./lb.

Superheater supplies heat = °F. superheat × specific heat

$= (765{\cdot}5 - 456{\cdot}5) \times 0{\cdot}63$

$= 189$ B.Th.U./lb.

Economiser supplies heat = °F. rise through economiser

$= 400 - 320$

$= 80$ B.Th.U./lb. approx.

or from steam tables $= (374 - 290)$

$= 84$ B.Th.U.

∴ Heat from boiler proper $= 1{,}102 - (189 + 84)$

$= 829$ B.Th.U./lb.

Assume coal supplied per hour is 17,000 at 10,000 B.Th.U./lb.

$$\text{then boiler efficiency} = \frac{\text{evaporation lb./hr.} \times \text{heat/lb.}}{\text{lb. of coal/hr.} \times \text{calorific value}}$$

$$= \frac{130{,}000 \times 1{,}102 \times 100}{17{,}000 \times 10{,}000}$$

$= 84{\cdot}5$ per cent.

If feedwater temperature falls to 300° F.

Heat input $= 1{,}390 - (300 - 32)$

$= 1{,}122$ B.Th.U./lb.

$$\text{For same conditions, coal/hr.} = \frac{130{,}000 \times 1{,}122 \times 100}{10{,}000 \times 84{\cdot}5}$$

$= 17{,}250$ lbs.

Assuming that the increased weight of flue gases to economiser raises feedwater temperature 90° F., then new economiser outlet temperature = 300 + 90
= 390° F.

$$\begin{aligned}
\text{Heat from boiler proper} &= H_s - h \\
&= 1{,}203 - 364 \\
&= 839 \text{ B.T.U./lb.} \\
\text{Heat from economiser} &= \;\;90 \quad ,, \\
\text{Total} &\quad \overline{\underline{929}} \\
\text{Heat from superheater} &= 1{,}122 - 929 \\
&= 193 \text{ B.T.U./lb.} \\
\text{Temp. rise, spec. heat} &= \text{B.Th.U./lb.} \\
\therefore \text{Temp. rise} &= \frac{193}{0{\cdot}63} \\
&= 307^\circ \text{ F.}
\end{aligned}$$

Showing a rise in superheat of 307 − 300 = 7° F. approx.

An actual case where a 130,000 lb./hr. 300 p.s.i. 750° F. boiler with feedwater at 160° F. had to operate with feedwater at 290° F. :—

Estimated reduction in steam temperature 25° F.
,, increase ,, leaving gas ,, = 25° F.
,, ,, ,, air ,, = 15° F.
Less coal required/hr.

For a reversal of the feed water conditions there would be an increased steam temperature and a reduction in the exit gas and pre-heated air temperature of about the same order but more coal would be required per hour.

High feedwater temperature necessitates a larger superheater if a boiler is to deliver the same quantity of steam at the same temperature as with lower feedwater temperature.

Auxiliary Plant. The auxiliaries are tested as far as possible under actual working conditions at the makers' works before delivery to site. Copies of the test certificates are forwarded to the engineer for his comments and approval. In some cases the engineer or his representative may attend the maker's works to witness such tests.

Switchgear, Transformers and Cables. The lower voltage switchgear and control panels, etc., are tested to ensure that the insulation

and connections are in order. Over-voltage tests are applied to the higher voltage switchgear and all connections checked. The makers provide a testing transformer the rating of which will depend on the plant to be tested. The rating may vary from 2 to 100 kV.A.

Transformers call for no special comment. High-voltage cables may be pressure tested after laying by applying an over-voltage D.C. test.

It is suggested in B.S.S. No. 81 that the testing of instrument transformers with a D.C. voltage is liable to introduce abnormal electric stresses and should only be undertaken by arrangement with the manufacturer.

Cranes, and Lifts. Are tested at the maker's works before delivery to site, but it will be necessary to try out all motions and make a general inspection after completion of erection. All interlocking and safety devices should be thoroughly tried before putting into commission. Cranes, lifts and other lifting equipment, like boilers, steam and air receivers must be periodically examined in accordance with the Factories Acts.

Typical Test Results. Typical test results taken on different items of plant may prove useful for reference purposes. In some examples only approximate figures are given.

TABLE 78. *Condenser Performance*

(*see Table* 77)

Load in kW. at 0·8 pf.	Steam Condensed lb. per hour	Cooling Water gallons per minute	Abs. Press Turbine Exhaust inch Hg.	Temp Condensate °F.	Cooling Water Inlet °F.	Cooling Water Outlet °F.
(11·0 kV.) 30,000	225,510	26,750	2·00	101·0	80	94·1
24,000	176,000	,,	1·75	96·6	,,	91·0
18,000	137,040	,,	1·60	93·7	,,	88·6
(33·0 kV.) 30,000	223,930	,,	2·00	101·0	,,	94·0
24,000	175,260	,,	1·75	96·6	,,	90·9
18,000	136,090	,,	1·60	93·7	,,	88·5

TABLE 79. *Condenser Test Results*

No. of test	1	2	3
Date	16/3/38	17/3/38	17/3/38
Nominal load—kW.	50,000	40,000	30,000
Steam condensed—lb. per hour	334,660	284,215	222,088
Steam pressure at stop valve—lb. per square inch	620	619·3	627·9
Steam temperature at stop valve—°F.	823·5	822	821
Degree of Superheat—°F.	331·2	329·8	327·3
Vacuum (Bar. 30″ Hg.)—inches Hg.	29·2	29·36	29·43
Temperature corresponding to vacuum—°F.	72·2	65·4	62·3
Condensate temperature—°F.	75	67·8	63·3
Temperature circulating water inlet—°F.	51·7	50·2	50·2
Temperature circulating water outlet—°F.	64·5	62·1	59·4
Rise—°F.	12·8	11·9	9·2
Heat in condensate above 32° F.—B.Th.U.	43	35·8	31·3
Latent heat in exhaust—B.Th.U.	922·7	925·7	917·2
Total heat in exhaust—B.Th.U.	962·8	959·3	947·7
Heat rejected to circulating water—B.Th.U.	919·8	923·5	916·4
Cooling surface—square feet	40,000	40,000	40,000
Mean temperature difference—°F	14·96	9·7	7·25
Transmission rate—B.Th.U. per square foot per °F per hour	504	676	702
Actual rate of heat transfer—B.Th.U. per square feet per hour	7,688	6,560	5,088
Ejector steam consumption Stage I.—lb. per hour	615	628	631
Ejector steam consumption Stage II.—lb. per hour	481	486	483
Ejector steam consumption Stage III.—lb. per hour	480	475	475
Ejector steam consumption total—lb. per hour	1,576	1,589	1,589
Ratio ejector consumption to total steam—per cent.	0·37	0·44	0·58

At the time of the tests the set was supplying load to a large network, and the readings were taken every five minutes for a period of two hours during which time the governor was continuously under the control of the operating engineer who kept a very steady load on the bus-bars.

The guaranteed vacua at the circulating water temperatures at the time of the tests are as follows: Barometer 30″ Hg. and the amount of circulating water constant.

100 per cent. load (50 MW)	29·10″ Hg.
80 ,, ,, (40 ,,)	29·25″ ,,
60 ,, ,, (30 ,,)	29·29″ ,,

From the test figures it will be observed that the actual exceeds the guaranteed Hg. 0·1″, 0·11″ and 0·14″ respectively. During the test air was admitted to the condenser at the turbine exhaust through the full bore of ½ inch air cock in an attempt to bring the vacuum nearer to the guaranteed figures, but the figures given on test were maintained. In normal service vacuum up to 29·5″ has been obtained at loads 60 to 80 per cent.

Heat Rejected to Condenser. This can be estimated by an approximate method as follows :—

Total steam condensed per hour . .	334,000 lb.
Steam consumption of turbine . .	7·8 lb. per kWh approx.
Initial pressure and temperature. .	620 lb. 820° F.
Heat in condensate . . .	43 B.Th.U. per lb.
Temperature rise of circulating water .	12·8° F.
Assumed alternator losses . . .	2·5 per cent.
Assumed bearing losses . . .	1·5 per cent.

Total heat in steam from 32° F. $= 1{,}418$ B.Th.U. per lb.

$$\text{Heat utilised in mechanical work} = \frac{3{,}412}{0{\cdot}96 \times 7{\cdot}8} = 455 \text{ B.Th.U. per lb.}$$

Heat rejected to circulating water

$$\begin{aligned} &= 1{,}418 - (\text{heat in condensate} + 455). \\ &= 1{,}418 - (75 - 32 + 455). \\ &= 1{,}418 - (43 + 455). \\ &= 920 \text{ B.Th.U. per lb. of steam condensed approximately.} \end{aligned}$$

The temperature rise of the circulating water is 12·8° F. The quantity of circulating water flowing through the condenser can be estimated as follows :—

For every lb. of steam condensed, each lb. of circulating water (assuming the specific heat of the water to be 1·0 at this temperature) carries away 12·8 B.Th.U.'s, therefore the ratio of circulating water to steam is 920 : 12·8 or 72 : 1.

$$\begin{aligned} \therefore \quad \text{total circulating water per hour} &= 334{,}000 \times 72 \\ &= 24{,}000{,}000 \text{ lb. per hour} \\ &= 40{,}000 \text{ gallons per minute.} \\ \text{The turbine thermal efficiency} &= \frac{455}{1{,}418} \\ &= 32 \text{ per cent. approx.} \end{aligned}$$

This should not be confused with the efficiency ratio or thermodynamic efficiency of the turbine.

$$\begin{aligned} \text{The efficiency ratio} &= \frac{\text{actual mechanical output at coupling}}{\text{mechanical work available from ideal turbine on Rankine cycle.}} \\ &= \frac{\text{heat equivalent to 1 kW. hour}}{\text{actual adiabatic heat drop.}} \\ &= \frac{3{,}412}{H_a} \end{aligned}$$

where $Ha = (H_1 - H_3)w.E_{ab}$

$(H_1 - H_3)$ = adiabatic heat drop per lb. of steam.

w = steam consumption lb. per kWh.

E_{ab} = 1·0 — (alternator losses + bearing losses).

This ratio covers all the internal losses such as blade and disc friction, fan losses, diaphragm or tip leakage, together with all external losses such as bearing friction, power absorbed by governor and oil pump drives, coupling windage, etc.

Taking the present example we get :—

Adiabatic heat drop per lb. of steam = 550 B.Th.U's (29·2 in. Hg.).

$$H_a = 550 \times 7{\cdot}8 \times 0{\cdot}96 = 4{,}130.$$

$$\text{Then efficiency ratio} = \frac{3{,}412}{4{,}130} = 82{\cdot}5 \text{ per cent. approx.}$$

TABLE 80. *Cooling Tower Performance*

(*See also Vol. I.*)

Plant in Service	Circulating Water: Entering Condenser °F.	Circulating Water: Leaving Condenser °F.	Circulating Water: Temp. Rise °F.	Circulating Water: Water through Condenser gallons per hour	Condensate lb. per hour	Ratio Water/Steam
No. 1 30 MW set	76·0	88·3	12·3	1,639,000	223,100	73·5
No. 2 30 MW set	76·5	86·5	10·0	1,841,800	211,800	87·0
Totals and averages	76·24	87·4	11·15	3,480,800	—	—

Wet Bulb Temp. °F.	Dry Bulb Temp. °F.	Humidity per cent.	Water to Tower °F.	Water from Tower °F.	Range of Cooling °F.	Guaranteed Re-cooled Temp. °F.
40·5	42·5	84·3	88·0	70·0	18·0	71·0

Observations : Wind velocity : 8·0 ft. per second.
Direction of wind : N.N.W.
Weather : Cold and fine (January).
Tower and pump valves : Fully open.
Period of test : Two hours.

Reinforced concrete cooling tower : 3,500,000 gallons per hour.

TABLE 81. *Boiler Test Results*

Pulverised Fuel Boiler. (Unit System.)

110,000 lb. per hour N.E.R. 730° F.
130,000 lb. per hour M.C.R. 750° F.
300 lb. per square inch

Feed Temperature at Economiser Inlet 170° F.

	Description		N.E.R.	M.C.R.
Total quantities.	Duration of test		24 h. 4 m.	24 h. 26 m.
	Water by venturi meter	lb.	2,683,548	3,163,830
	Water evaporated by boiler	,,	2,652,384	3,127,045
	Fuel fed to Mills	,,	345,975	453,012
Average pressures.	Steam pressure, boiler drum	lb. per square inch	317·6	322·8
	,, ,, superheater outlet	,, ,, ,,	298·9	297·9
	Drop through superheater	,, ,, ,,	18·7	24·9
	Air at heater inlet	in. W.G.	2·8	3·8
	,, ,, outlet	,, ,,	1·2	1·6
	Air drop through heater	,, ,,	1·6	2·2
	Secondary air to burners	,, ,,	0·7	0·72
	Primary air and coal, No. 1 burner	,, ,,	3·0	2·9
	,, ,, ,, No. 2 ,,	,, ,,	2·7	2·9
	,, ,, ,, No. 3 ,,	,, ,,	2·7	2·8
Average temperatures.	Saturated steam (calculated)	°F.	427·2	428·2
	Superheated steam	,,	737·9	770·7
	Superheat	,,	310·7	340·5
	Feed to economiser	,,	160 8	162 8
	Feed to boiler	,,	205 5	211·4
	Rise in feed through economiser	,,	44·7	48·6
	Flue gas: Boiler outlet	,,	653 0	706·0
	,, ,, Economiser outlet	,,	521 0	569·0
	,, ,, Heater outlet	,,	310 0	327·0
	Air in B.H. at F.D. fan	,,	84·0	83 0
	Air entering heater	,,	144 0	144 0
	,, leaving heater	,,	386·0	410 0
	Rise in air through heater	,,	302·0	327·0
	Fall in gas through economiser	,,	132 0	137·0
	,, ,, ,, ,, heater	,,	211 0	242·0
	Primary air and coal No. 1 burner	,,	156·0	140 0
	,, ,, ,, No. 2 ,,	,,	156·0	152·0
	,, ,, ,, No. 3 ,,	,,	160·0	154·0
Average draughts.	Combustion chamber	in. W.G.	0 07	0·09
	Boiler outlet	,,	0·90	1·42
	Economiser outlet	,,	1·10	1·60
	Heater outlet	,,	1·90	2·90
	Loss through boiler	,,	0 83	1·31
	,, ,, economiser	,,	0·20	0·22
	,, ,, heater	,,	0·80	1·30

TABLE 81—*continued*

	Description	N.E.R.	M.C.R.
Products of combustion.	CO_2 at heater outlet . . . . per cent.	13·5	13·6
	O_2 " " " . . . . . "	5·8	6·0
	CO " " " . . . . . "	0·0	0·0
	Moisture in fuel per lb. of fuel . . lb.	0·1036	0·1430
	Moisture of combustion per lb. of fuel . "	0 3582	0·3357
	Dry gas per lb. of fuel . . . . . "	11·4354	10·733
Electrical meters.	No. 1 mill drive motor current . amps.	109	111
	No. 2 " " " " . . . . "	93	96
	No. 3 " " " " . . . . "	91	91
	No. 1 " Feeder " " . . . . "	0·9	0·9
	No. 2 " " " " . . . . "	0·9	0·9
	No. 3 " " " " . . . . "	1·0	1·0
	F.D. Fan motor current . . . . . "	71	93
	I.D. " " " . . . . . "	74	111
	Other auxiliaries . . . . . . "	47	48
	A.C. voltage . . . . . . volts.	401	404
	D.C. " . . . . "	474	476
Hourly quantities.	A.C. total meter . . . . . kWh.	4,700	4,885
	D.C. " " . . . . . . "	1,689	2,347
	Water evaporated . . . . . . lb.	110,210	127,982
	Fuel fired . . . . "	14,376	18,548
	Water evaporated per lb. of fuel . . "	7·666	6·903
	Factor of evaporation . . . . . "	1·30	1·315
	Equivalent evaporation . . . . . "	143,273	168,296
	" " per lb. of fuel . "	9·966	9·077
	Weight of flue gas and moisture . . "	171,034	207,960

The coal was sampled in accordance with B.S.S. 735

The water evaporated was measured by venturi meter, corrections being made in accordance with the calibrations noted at makers' works.

Steam and water temperatures were measured by mercury in glass N.P.L. certified thermometer, gas and air temperatures by thermometers or thermocouple outfits and the gases analysed by Orsat apparatus.

The power consumption was measured by integrating kWh. meters.

Samples of ash and dust were taken for analysis, but it was not possible to weigh the quantities of ash and dust collected.

Samples of the pulverised fuel were also taken for moisture and fineness determinations.

The coal analysis represent average values.

Heating surfaces.

Boiler	11,510 sq. ft.
Combustion chamber . .	2,550 "
Superheater	4,250 "
Economiser	1,830 "
Air heater	23,962 "
Volume of combustion chamber .	9,340 cubic ft.

TABLE 81—*continued*

	Description		N.E.R.	M.C.R.
Proximate analysis.	Moisture	per cent.	10·36	14·30
	Volatile matter	,,	30·25	28·84
	Fixed carbon	,,	46·48	44·65
	Ash	,,	12·91	12·21
	Gross calorific value	B.Th.U./lb.	11,043	10,356
Ultimate analysis.	Carbon	per cent.	62·24	58·69
	Hydrogen	,,	3·98	3·73
	Nitrogen	,,	1·32	1·22
	Sulphur	,,	1·09	1·25
	Oxygen	,,	8·10	8·60
	Moisture	,,	10·36	14·30
	Ash	,,	12·91	12·21
	Net calorific value	B.Th.U./lb.	10,556	9,801
Pulverised coal.	Moisture, No. 1 Mill	per cent.	3·5	6·1
	,, No. 2 ,,	,,	2·8	4·9
	,, No. 3 ,,	,,	3·1	4·5
	Grading No. 1 Mill, minus 44 B.S.S.	,,	99·3	98·0
	,, ,, ,, ,, 100 ,,	,,	87·9	78·2
	,, ,, ,, ,, 200 ,,	,,	61·0	47·8
	Similar results for Nos. 2 and 3 mills (approx.)			
Ash from combustion chamber : Combustible matter (dry)		per cent.	1·9	1·9
Dust from precipitator : Combustible matter (dry)		,,	11 4	9·6

N.E. Rating : 345,975 lb. in 24 hours approx.

$$\text{Total Heat Input} = \frac{345{,}975}{24} \times 11{,}043 \text{ B.Th.Us. per hour}$$

$$\text{Heat Equivalent of Auxiliary Power} \quad \text{HE} = \frac{345{,}975 \times 11{,}043 \times 2{\cdot}52}{24 \times 266}$$

$$\simeq 15{,}000 \text{ B.Th.U. per kW.}$$

$$\text{Auxiliary Power as Percentage of Heat Input} = \frac{\text{kW} \times \text{HE}}{\text{lb. coal per hr.} \times \text{CV}} \times 100.$$

TABLE 81—*continued*

	Conclusions	N.E.R.	M.C.R.
Furnace, boiler and superheater.	Heat liberated per cubic foot furnace volume . . B.Th.U. per hour	16,650	21,200
	Air supplied per lb. of coal . . . . lb.	11·041	10·346
	Air theoretically required per lb. of coal . lb.	8 076	7·602
	Ratio : Excess air	1·365	1·36
	Heat added to water in boiler. B.Th.U. per lb.	1081·1	1079·1
	Heat transfer per square foot water to heating surface . . . B.Th.U. per hour	8,485	9,825
	Heat added to steam in superheater B.Th.U. per lb.	181·1	197·6
	Heat transfer per square foot superheating surface . . . B.Th.U. per hour	4,700	5,900
Economiser and Air Heater.	Economiser : Heat transfer per square foot heating surface per ° F. log. mean temperature difference . . . B.Th.U. per hour	6·69	7·55
	Air heater : Ditto . . . ,, ,,	2·14	2·64
Power consumption.	No. 1. Mill and feeder . . . . kW.	72·7	74·0
	No. 2. ,, ,, ... ,,	62·2	64·1
	No. 3. ,, ,, ... ,,	60 9	60·9
	F.D. fan . . . . ,,	34·8	43·9
	I.D. ,, ... ,,	35·6	52·1
	Total power . . . . . kW. per hour	266	295
	Total power as per cent. of heat input per cent.	2 52	2·31
Heat account. Gross overall thermal efficiency.	Heat leaving plant in steam : Gross overall thermal efficiency of unit . . per cent.	87·63	85·11
	Heat lost in :		
	Moisture in fuel . . . . per cent.	1·08	1·59
	Moisture of combustion . . ,,	3 71	3·75
	Dry products of combustion . ,,	4 10	4·48
	Excess air . . . . . . ,,	1·46	1·57
	Combustible in ash and dust : Radiation and balance of account . . . . ,,	2·02	3·50
	Heat entering plant (gross calorific value) . .	100·00	100 00
	Gross overall thermal efficiency of unit on net calorific value . . . . per cent.	91·80	89·80

TABLE 82. *Electrostatic Precipitator Test Results*

Description	Guarantee N.E.R.	Guarantee M.C.R.	Test No. 1	Test No. 2
Duration of test . . . . .hours	—	—	3	2
Water evaporated . . . . lb. per hour	110,000	130,000	114,233	117.209
Steam temperature . . . . °F.	730	750	719	734
,, pressure . . . . lb. per square inch	300	300	313	311
Feed temperature economiser inlet . . . . . . °F.	170	170	154	160
Gas temperature precipitator inlet . . . . . . °F.	285	310	283	295
,, ,, ,, outlet . . . . . . °F.	—	—	247	259
CO_2 ,, inlet . . . . . per cent.	13·3	13·3	14·3	14·4
,, ,, outlet . . . . . ,,	—	—	14·0	14·0
Volume of gas sampled " P " inlet . cubic feet per minute N.T.P.	—	—	2,479	13,000
Dust collected . . . . grams	—	—	264	189
Dust burden . . . . . . grains per cubic foot N.T.P.	—	—	3·5	3·43
Volume of gas sampled, " P " outlet cubic foot per minute N.T.P.	—	—	2,280	1,520
Dust collected . . . . grams	—	—	18	10
Dust burden . . . . . grains per cubic foot N.T.P.	—	—	0·122	0·101
Total velocity by pitot . . . . . cubic feet per minute	—	—	66,500–283 °F.	69,000–295 °F.
Precipitator efficiency. . . . . per cent.	95	92·5	96·5	97·14

The efficiency of other types of grit arrestors as used in stoker-fired plants usually varies between 73 and 86 per cent. although higher figures are sometimes claimed.

Table 83. *Crane Test Results*

75-ton Overhead Crane. Four-motor Type. 61 ft. Span.

	Motion	Load T.	Load C.	Load Q.	Load L.	Speed ft. per minute
Heavy hoist.	Normal Up	—	—	—	—	7·4
	,,	35	—	—	—	5·7
	,,	45	—	—	—	4·9
	,,	75	—	—	—	4·2
	,,	112	10	—	—	3·65
	Down	—	—	—	—	7·5
	,,	35	—	—	—	7·7
	,,	45	—	—	—	8·0
	,,	75	—	—	—	8·2
	,,	112	10	—	—	8·6
Light hoist	Up	—	—	—	—	25·0
	,,	25	—	—	—	13·2
	Down	—	—	—	—	25·0
	,,	25	—	—	—	27·7
Cross travel	Normal	—	—	—	—	150·0
	,,	45	—	—	—	68·0
	,,	75	—	—	—	58·0
	,,	112	10	—	—	48·0
	Dead slow	—	—	—	—	8·0
	,,	35	—	—	—	4·3
	,,	75	—	—	—	8·8

	Motion	Load T.	Load C.	Load Q.	Load L.	Speed ft. per minute
Heavy hoist.	Dead slow Up	—	—	—	—	0·76
	,,	35	—	—	—	1·35
	,,	75	—	—	—	0·45
	Down	—	—	—	—	0·76
	,,	35	—	—	—	1·02
	,,	75	—	—	—	0·40
	,,	75	—	—	—	1·24
Main travel.	Operated in both directions with all loads and found in order at both normal and dead slow controls.					

Remarks:
Deflection of main girders under full load . . . . $\frac{7}{16}$ in.
Ditto test load . . . $\frac{5}{8}$ in.

Overall I.R. test — 6 megohms
The voltage was observed and current readings were noted for each speed.
Diverter control fitted.

Guarantees:			
Heavy hoist with F.L.	(75_T)	4 ft. per min.	30 B.H.P.
Light ,, ,, ,,	(25_T)	12 ,, ,, ,,	30 ,,
Cross travel ,, ,,	(75_T)	50 ,, ,, ,,	10 ,,
Main ,, ,, ,,	(75_T)	100 ,, ,, ,,	22 ,,

Comparisons:

40-ton Crane

With two-wheel end carriages.
Load on one travelling wheel, 30 tons.
Centres of wheels, 12 ft. 6 in.
Reaction on one gantry, 60 tons.

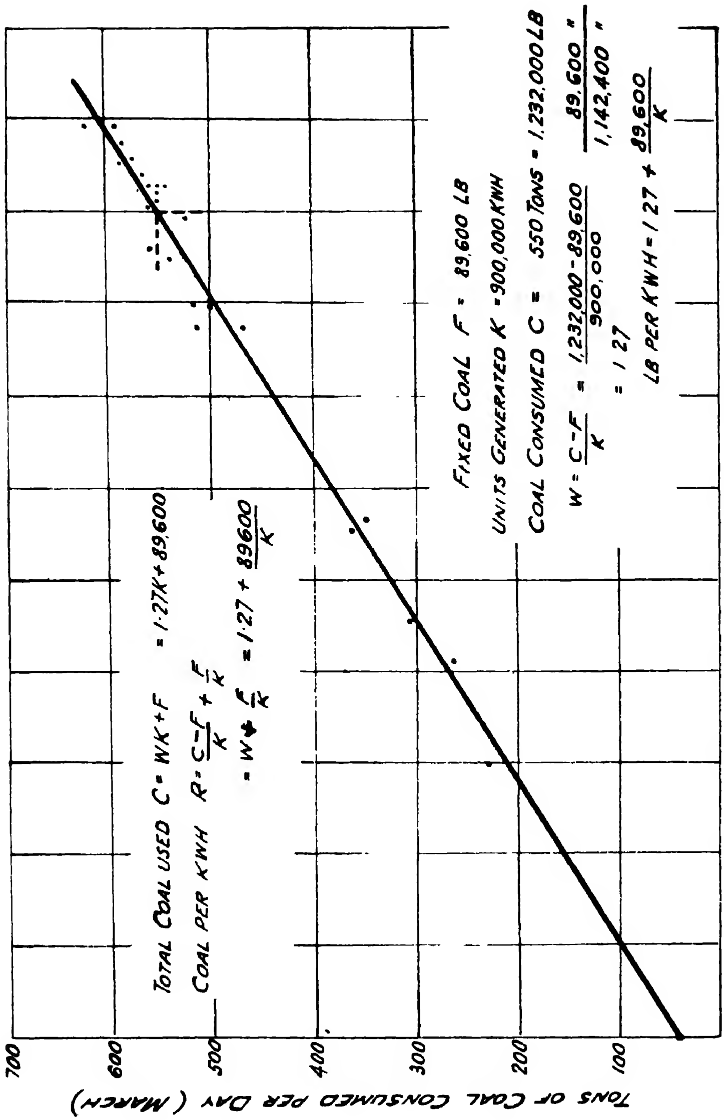

FIG. 540. Willans' Coal Line.

75-ton Crane

With four-wheel end carriages.
Load on one travelling wheel, 27 tons.
Centres of wheels—Inner, 6 ft. 6 in.
Outer, 19 ft. 6 in.
Reaction on one gantry, 108 tons.

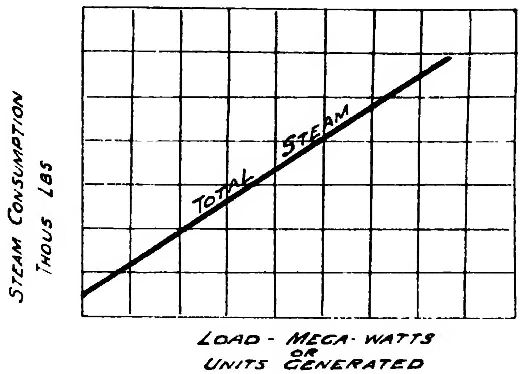

FIG. 541. Willans' Steam Line.

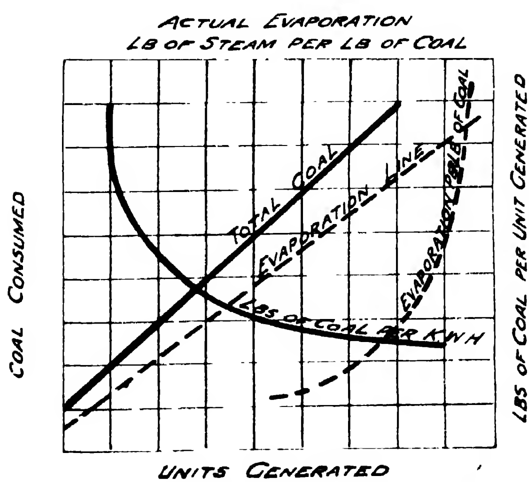

FIG. 542. Willans' Coal and Water Lines.

The graded load curve or load duration curve, Fig. 543, which is made up of the load on the system and the running hours shows that the maximum load obtains for a relatively short period of time, usually a few days in the winter. The curve shows by means of the horizontal lines the amount of load which is allocated to each power station or machine as the case may be and it will be noted that the

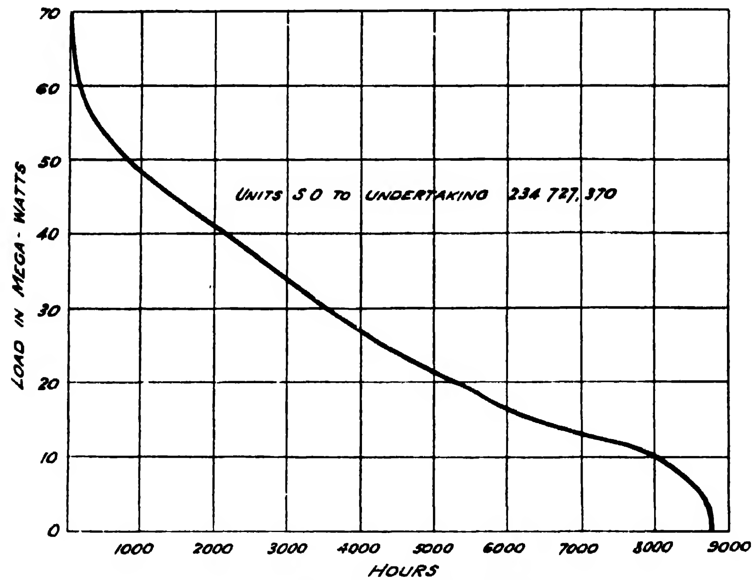

FIG. 543. Graded Load Curve.

period of time when it is necessary to run all generating plant is comparatively short and that some plants or machines will only run for a moderate length of time. The base load at the bottom of the curve is met by the most efficient plant running continuously throughout the year. Some power stations may have no load to meet until peak periods and in consequence are shut down for considerable periods. The allocation of electrical load throughout the day is in accordance with a predetermined operating schedule based on the cost of production of the plants or machines.

OVER-VOLTAGE TESTS ON SWITCHGEAR

THREE-PHASE 33 kV.—750 MVA METAL-CLAD SWITCHGEAR

Date of test ....

Present.................................

Testing Equipment

The contractor supplied the transformer of 2 kVA. capacity 0/52 kV. and spark gap (spheres 62·5 mm.).

A single-phase 420-volt (1·8 amps.) supply was given.

The spark gap was adjusted to jump at about 43 kV.

I.R. Tests

Before application of over-voltage	.	Over 100 megohms.
After ,, ,, ,, .	.	,, ,, ,,

(500-volt Megger).

Over-voltage Tests (Bottom Bus-bars)

Test 1.	Blue phase	—43 kV.	—R and Y	phases	earthed.
,, 2.	Yellow ,,	—43 ,,	—R ,, B	,,	,,
,, 3.	Red ,,	—42 ,,	—B ,, Y	,,	,,

These voltages were maintained for one minute.

A limited voltage of 45 kV. was agreed due to the top bus-bars and the isolators being alive.

TESTS ON 11 kV. CABLES AND REACTOR

Date of test ....

Present...............................

Testing Equipment

A high-pressure direct current testing set was used. A sphere gap adjusted for a breakdown voltage of 22 kV. was connected across the testing set terminals.

Particulars of apparatus, etc., under test : Cables between 11 kV. switchboard panel No. 1 and main transformer No. 1 comprising 4/0·75 sq. in. single-core cables per phase, including a 3,750 kVA. three-phase reactor.

Over-voltage Tests

A voltage of 20 kV. D.C. was applied between each phase and earth for fifteen minutes, the other two phases being earthed. The leakage was measured in each case, the readings obtained were as follows :

Phase	Current Leakage	Corresponding I.R.
	m.A.	megohms
Red	0·35	57
Yellow . . .	0·20	180
Blue	0·35	57

No variation in these values was observed during the voltage tests. The somewhat high value was due to the cables at the transformer end being terminated in outdoor porcelains and probably aggravated by moist atmosphere caused by the nearby cooling towers.

Insulation Resistance

	Before Testing	After Testing
	megohms	megohms
Red phase . . .	100	50
Yellow ,, . . .	75	70
Blue ,, . . .	75	50

The method of supporting the outside connections was varied during the period before and after testing and this has affected the I.R. valves.

Miscellaneous Tests

The cables were phased out and found in order. The resistance of the reactor tank to earth was measured and found to be approximately 250 ohms under dry conditions.

Test Charts. Figs. 540 to 543 indicate some of the curves and charts which may be prepared to assist in the maintenance of a highly efficient power plant.

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CHAPTER XXI

ORGANISATION

THE fundamentals of organisation were briefly outlined in Volume I, and it will be appreciated that as with power plant, so with station staffs and workmen, no hard and fast rules can be made which will apply to all stations. Any personnel scheme however well developed depends on the goodwill of the staff involved, as overlapping is sometimes unavoidable. The organisation will vary according to the size and type of undertaking together with the immediate and future requirements regarding extensions. The general practice followed by former power companies, joint authorities and large municipal undertakings was to have a permanent construction staff to handle power station extensions. In some cases, however, the assistance of consulting engineers is sought for specialised works. Where an undertaking controls a number of stations it is usual to have a generation or power stations' engineer who is responsible for the operation and maintenance of the stations and who also takes a leading part in extensions and new stations. Some large power companies had a head office staff embodying civil, mechanical and electrical engineering sections, dealing chiefly with power stations. A typical example being :—Chief Civil Engineer; Chief Constructional Engineer; Chief Generation Engineer; Chief Electrical Engineer.

As far as the construction side is concerned it is possible for the work to be carried out by two sections, a civil and mechanical constructional engineer and an electrical constructional engineer. In small and medium size undertakings it is possible for the chief constructional engineer to deal with civil, mechanical and electrical engineering matters associated with power stations. With the advent of nationalisation of the supply industry in this country, numbers of power stations are grouped under Divisional Controllers, who each have a Chief Generation Engineer (Operation) and a Chief Generation Engineer (Construction) under him. Further sub-division provides for Group Generation Engineers for both Operation and Construction.

Construction Department. Since the construction department plays an important part in power station design and layout which in turn affects operation, a few notes concerning its organisation and working are included. This department is responsible for the general

design, layout and construction of power station plant and buildings. The preparation of specifications, which in itself is no small job, is

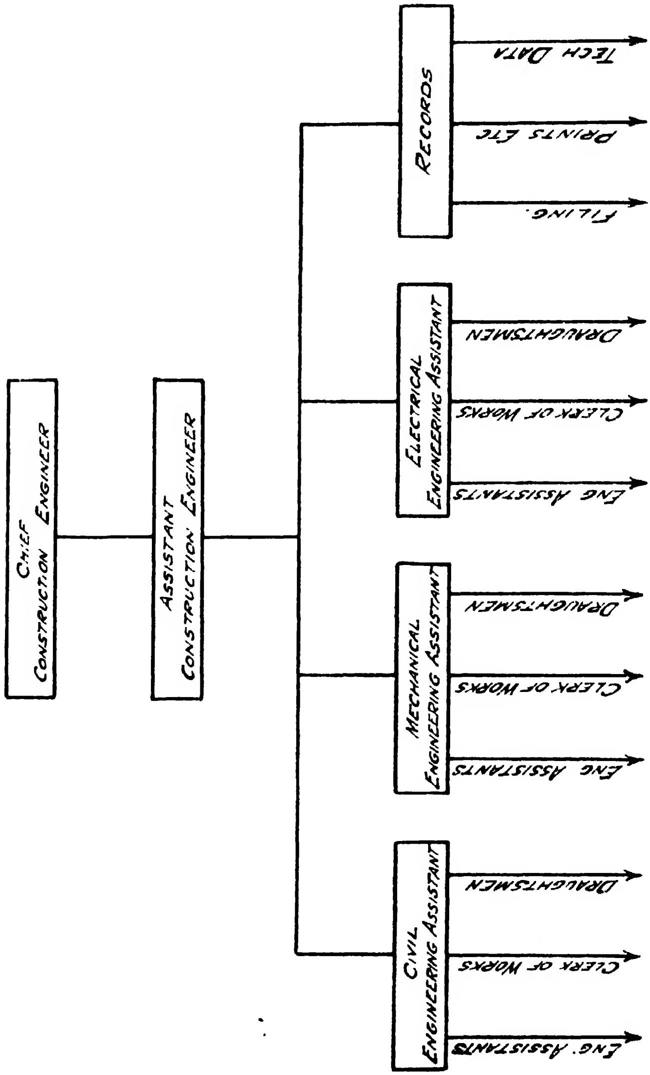

Fig. 544. Construction Department Organisation.

also undertaken. A design and drawing office is probably the most important section of this department and the staffing and organisation of such an office calls for special attention. This department

deals with electrical, mechanical and civil engineering works. A wide and varied experience in all three branches is essential if a chief is expected to carry out these works. A typical organisation diagram for such a department is shown in Fig. 544.

Station Organisation. The station organisation may be broadly divided into three sections, namely, operation, maintenance, and records, as indicated in Fig. 545. The stations now being built

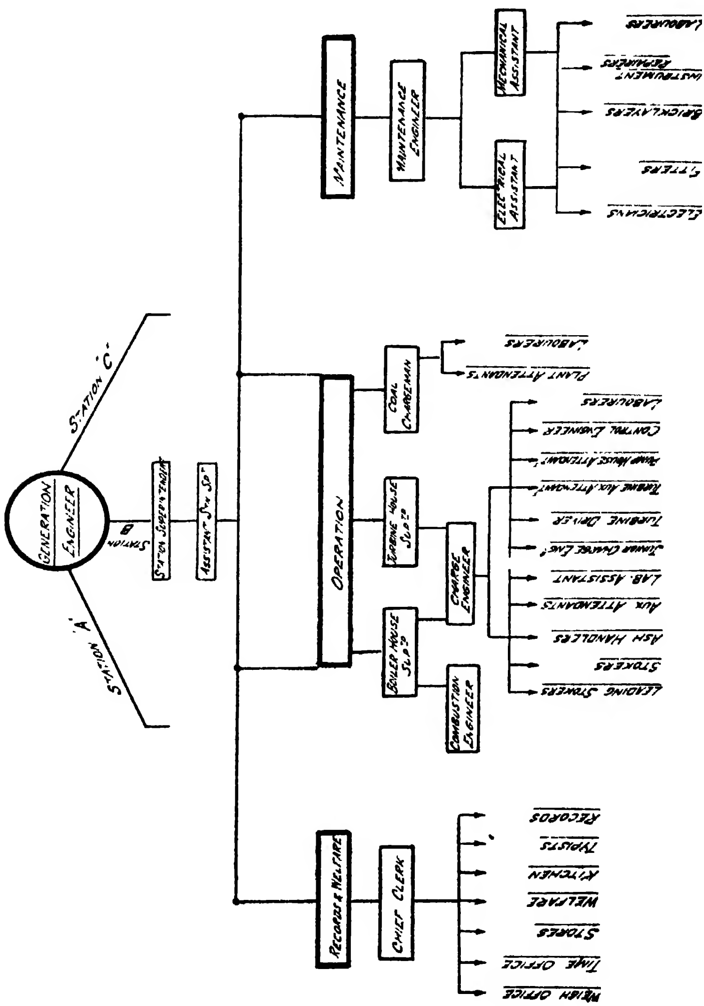

Fig. 545. Power Station Organisation.

house plants of large outputs and operate at high pressures and temperatures whilst extra high voltages are now quite common. The function of the power station is to produce electricity at the lowest possible cost, bearing in mind reliability, and although primarily concerned with electricity, the majority of work undertaken in a station is of a mechanical nature. As a matter of fact, a station is dependent not only on electrical and mechanical engineering for efficient operation, but also to a great extent on the work of the chemist.

The station superintendent is responsible for the management of the station and should also attend meetings, etc., in connection with any plant extensions. In a large station he may have the help of an assistant station superintendent who would attend to general matters concerning operation and relieve the station superintendent of much routine work. Where an assistant station superintendent is not employed it is usual to divide the boiler and turbine house work into two sections and appoint a boiler house superintendent and a turbine house superintendent. The boiler house superintendent would be responsible for all staff and plant in the boiler houses and probably the coal handling plant. He would supervise all important tests and draw up operation and maintenance programmes and generally instruct the staff. The duties of the turbine house superintendent would be similar, but apply only to the turbine house staff and plant and would generally include the supervision, inspection, maintenance, and testing of generation switchgear, etc. An alternative is the appointment of electrical and mechanical superintendents as assistants to the station superintendent. Next to the turbine house and boiler house superintendents the shift charge engineers are the principal assistants. In very large stations it is usual to have both boiler house and turbine house charge engineers. The subordinate staff may be summarised as follows :—

Turbine house (Shift staff)	Turbine drivers. Auxiliary plant attendants.
Boiler house (Shift staff)	Combustion engineer. Leading stoker. Stokers. Auxiliary plant attendants. Ash plant attendants. Coal plant attendants.
Control room (Shift staff)	Senior control engineer. Junior control engineer.

A number of spare auxiliary plant attendants and labourers are employed for general day shift working. The largest day shift staff comes under the supervision of the Maintenance and Repairs engineer. With the advent of large capacity stations and larger individual units it has been contended that the employees in the turbine and boiler houses have increased responsibilities which are not in any way reduced by the supervision of technical staff or by the fact that modern plant aids running at the highest efficiency. In such stations the increased number of important auxiliaries and instruments does necessitate a higher degree of intelligence, greater skill and knowledge, but does not apply to all grades or classes of operatives. Speaking generally, the majority of the work is of a mechanical nature, although electrical maintenance may be covered by the inclusion of an assistant electrical maintenance engineer. Maintenance has been described as that part of routine which maintains efficiency. A good test of efficiency of the maintenance department is its behaviour in an emergency, *e.g.*, the expediency with which the plant is put into service after a sudden and unexpected breakdown.

The repairs and maintenance department would include fitters, machine operators, blacksmith, electricians, electrical fitters, instrument fitters, joiners, bricklayers, boiler maintenance gang for tubing, general labourers, etc. A station clerk would be responsible for all clerical work including records, timekeeping, weigh office and probably the welfare department. The actual duties will, of course, vary according to circumstances. The clerical and welfare staff would include records clerk, returns clerk, general clerks for time office and weigh office, stores clerk and assistants, welfare workers including kitchen assistants, etc.

In a small station the stores department may also come under the direction of the station clerk in so far as records, orders, etc., are concerned, or alternatively under the central stores department. For a very large station the stores department would normally function as an independant section. A large proportion of the stores stock will be for repairs and maintenance so that the maintenance engineer should be able to advise on certain items.

It is necessary to have a chemist at any station unless a consulting chemist is retained, the general fuel analyses, etc., then being carried out by a junior, under the supervision of the boiler house superintendent. The staff in a large station will include a chemist with laboratory assistants and samplers. In some cases

the head of this department is termed chemist and testing engineer although a testing department is often established apart from the chemist.

Some idea will be obtained of the staffing from the following which refers to a typical 150 MW station (5–30 MW sets) :—

	Operation	Repairs and Maintenance	Clerical	Miscellaneous	Total
Salaried Staff . .	19	5	20	5	49
Manual Workers . .	117	136	—	6	259
TOTAL	136	141	20	11	308

The clerical staff includes work concerning accountancy, wages, stores, etc. and the average annual station loadfactor is 50 per cent.

Special Staff. The inclusion of fire-fighting and air raid precautions equipment necessitates the training of a special staff. Usually a senior officer is appointed who has control of a volunteer staff which is drawn from various sections of the undertaking. It will be appreciated that a great deal will depend upon the size and class of undertaking in so far as the organisation of such a staff can be determined.

Station Records. The accumulation of large numbers of records and log sheets is inevitable, but by systematic weeding much of this can be eliminated and only those records which are of particular importance need be retained for reference. The staff should be interested in the obtaining, keeping and making use of the records for the operation of the plant. Some of the log sheets met with are given for reference purposes, although much will depend on the types of plant installed and the organisation. A knowledge of the principal working results adds greatly to the interest which the operatives take in their work and the time spent in preparing, tabulating and plotting of graphs, etc., will in the end prove well worth while. In some instances the traction supply—trams and trolley buses—is given direct from the power station, and it is obligatory to keep a record of the rail drop and live line tests on the various routes. The general practice is to retain such records for a year.

The various recording charts required for the many items of

plant will be followed on referring to the instrument sections of the previous chapters.

Aids to Production. There are many ways in which the station personnel may be trained and maintained in a high state of efficiency, and it is up to the management to utilise every possible source however small. It is this attention to detail in the human factor which results in a contented staff and will inevitably be reflected in plant efficiency. As an example it is possible to educate the staff and operatives by means of simplified line diagrams so commonly met in electrical plant. As far as mechanical plant is concerned, little or no attempt has been made to exhibit the same degree of thoroughness. The drawing of unnecessary diagrams is not to be encouraged, but it should be borne in mind that what appears to the initiated to be superfluous may often prove to be the operatives' last word in portraying the plant under his care. This is often the case in practice where an engineering assistant who is familiar with a job fails to realise the type of operator who may be called upon to be responsible for the operation of the plant in question and whose training has been elementary in so far as engineering is concerned. This is not always the case, but it should be remembered that some of the operatives may move up into three or even four posts during the normal life of the plant.

If the diagrams are made during an early stage of a contract they also serve as progress charts by the use of suitable colour schemes. There are really no items of plant which cannot be drawn in diagrammatic form and even throughout the construction period will more than justify the cost incurred. During the design and layout of a station such diagrams are very helpful for reference at progress meetings and the amount of time saved is considerable. Moreover, where extensions are likely to take place at an early date, a great deal of time will be saved from their use.

So far as the senior and junior engineers are concerned, there is usually little difficulty and only the important diagrams are necessary, unless a set is required for the instruction of the operatives. The size of such diagrams is also worthy of some consideration and in practice foolscap has proved convenient. In addition, it is essential that all such diagrams and drawings be given a reference number so that any further copies can be obtained without recourse to searching through a heap of unfiled papers or tracings. The diagrams may be mounted on cardboard and gummed or varnished to prevent deterioration due to moisture.

The operation of a turbine calls for little comment, and providing certain duties are fulfilled there is nothing of exceptional importance. The makers generally supply a full description together with a number of drawings, and the operatives should be made responsible to gain a thorough knowledge of its functions as quickly as possible.

The senior turbine driver is responsible for its operation and is often a person of proved ability in so far as this class of work is concerned. He has the assistance of a junior driver or auxiliary plant attendant. The operation of boiler plant varies, depending on whether stoker or pulverised fuel firing is employed. It is possible that a station may benefit from local engineering concerns by way of recruitment of adaptable operatives much above the average. With a little encouragement such men have risen to junior and senior boiler operatives and also proved useful to the maintenance department. Such instances as outlined may prove useful to those who are endeavouring to interest the staffs and employees of electricity supply undertakings. The facilities provided should not be taken to suggest that the fact of handing over all the information relating to a job relieves a senior from his responsibilities. It is found that the provision of line diagrams fosters goodwill and team spirit which are essential to efficient co-operation. Typical line diagrams have been included throughout the various chapters to which reference can be made. By continual improvement in engineering design the laborious and manual tasks met with in early days have been reduced and the workers' duties are becoming more and more a question of accurate observation and control of working conditions, chiefly by way of electrical equipment.

STATION WEEKLY SUMMARY

Details for Week ending Sunday Midnight..........................

SUPPLY	UNITS	PER CENT.	MAX. LOADS kW.	TIME	DAY AND DATE
(1) E.H.T. 3-Phase . .					
(2) H.T. 1-Phase . . .					
(3) D.C. Power and Lighting .					
(4) D.C. Traction . . .					
(5) Works Supply . .					
(6) Generated . . .					
Local Demand (1–5) . .					

SUPPLY (EXTERNAL)	UNITS IMPORTED	UNITS EXPORTED	EXCESS TO IMPORT	EXCESS TO EXPORT	MAX IMPORT	MAX EXPORT

Max. Load corresponding period last year Gen...... ....Per cent Increase.......... ....

" " " " " " L.D.......... .. .. " " " ... .

Units Gen. corresponding period last year Gen........................ " " " .. ..

" " " " " " L D..................... .. " ....

STATION OPERATION		
TOTAL HOURS		
RUNNING UP	ON LOAD	SHUT DOWN

WORKS AUXILIARY POWER

			AUX. UNITS—RUNNING		AUX. UNITS—SHUT DOWN	
TOTAL A.C. UNITS	ACTUAL		A.C.		A.C.	
	PER CENT. ADDED					
TOTAL D.C. UNITS	ACTUAL		D.C.		D.C.	
	PER CENT. ADDED					

PLANT RUNNING HOURS

Motor Converters			Rotary Converters			Turbo Alternators				Evaporators			Softener	
1	2	3	1	2	3	1	2	3	4	1	2	3	Output Galls.	Salt Cwts.

Boiler Steaming Hours									Water Evap. Lb.	Water Evap. per Unit Gen. Lb.
1	2	3	4	5	6	7	8	9		

MILLING PLANT RUNNING HOURS

No. 2 House Mills (Boilers 1—5)			No. 6 Boiler			No. 7 Boiler			No. 8 Boiler			No. 9 Boiler		
No. 1	No. 2	No. 3	1	2	3	4	5	6	7	8	9	10	11	12

Feed Water Temp. °F.		Average T.S.V. Pressure	Average T.S.V. Temp °F	Average Superheat T.S.V. °F.	Average Vacuum Ins Hg. Abs.				Make-up Galls.		Fuel Oil Galls.	
Inlet	Outlet				1	2	3	4	Per Cent.		Used	
									Gross		Stock	

Bunker Stock	Tons	Coal Used	Tons	Coal per Unit Gen. Lb.	Ash and Dust Account					
					Gross Tons Ash	Gross Tons Dust	Lab. per Cent.	Actual per Cent.	Dust Fans Hrs. Run No. 1	Dust Fans Hrs. Run No. 2
No. 1 House =		No. 1 House =								
No. 2 House =		No. 2 House =								
Total =		Total =								

Station Load Factor =
Station Running Load Factor =
Calorific Value—B.T.U./Lb. =
Overall Thermal Efficiency =

Remarks :—

N B —This sheet can also be used for Monthly, Quarterly and Yearly Returns.

WELLFIELD CORPORATION ELECTRICITY DEPT.

DROVE ROAD POWER STATION

To THE CHIEF WAGES CLERK ....19 .

OPERATION SERVICES

Strength return for week ending ....
Hourly-paid staff, males ....
Weekly staff, males ....
Monthly staff, males...
Plus on loan From Repairs and Maintenance Dept. ....
From ....
From ....

Less Absent through sickness or accident ....
On annual holiday ....
On loan to Repairs and Maintenance Dept..................
On loan to ....

Nett working strength................................

Signed......................................
Station Superintendent.

DROVE ROAD POWER STATION

To GENERATION ENGINEER ....19 .
THE CHIEF WAGES CLERK

OVERTIME REPORT

Week ending............................

Weekly Summary of Overtime

Operation		Repairs and Maintenance	
	Totals		Totals
Actual hours worked .		Actual hours worked .	
Added hours . .		Added hours . .	
Total hours paid		Total hours paid	
	£ *s.* *d.*		£ *s.* *d.*
Total wages paid . .		Total wages paid .	

Totals for Station

Actual hours worked	
Added hours	
Total hours paid	
	£ *s.* *d.*
Total wages paid	

Signed..................................

Station Superintendent.

PLANT RECORD

Job No. 3/3.
Sheet No. 1.

Section. No. 3 RAYMOND MILL AND EXHAUSTER

Particulars. Type : 5-roller Raymond mill.
Capacity : 15 tons per hour.
Direct coupled.
Installed June, 1933.

Date	Records	Initial
	Mill Overhaul.	
20/3/34	Bull Ring renewed. Hours run, 1,738. Approximate output, 1,738 × 9·5 = 16,511 tons. One pendulum changed ; Silent Bloc Bush defective. Four rollers in fairly good condition.	J.P. & S.H.
25/3/34	Exhauster Fan Impeller and casing scaled. Bearing assembled with new Roller Bearing at back end. New Housing required.	W.D.E.
	The Continuation Sheets have only Job No. and Sheet No.	

Cycle of Shifts

NIGHTS . .	A	SAT. (12—8)	SUN.	MON.	TUES.	WED.	THURS.	FRI.
EVENINGS . .	B	MON. (4—12)	TUES.	WED.	THURS.	FRI.	SAT.	SUN.
DAYS . . .	C	MON. (OFF)	TUES. (8—4)	WED.	THURS	FRI.	SAT.	SUN.
SPARE . .	D	MON. (SHIFT) (8—4)	TUES. (OFF)	WED. (9—5)	THURS. (9—5)	FRI. (9—5)	—	—
EVENINGS . .	A	MON. (4—12)	TUES.	WED.	THURS	FRI.	SAT.	SUN.
DAYS . . .	B	MON (OFF)	TUES. (8—4)	WED.	THURS.	FRI.	SAT.	SUN.
SPARE . . .	C	MON (SHIFT) (8—4)	TUES. (OFF)	WED (9—5)	THURS. (9—5)	FRI (9—5)	—	—
NIGHTS . .	D	SAT. (12—8)	SUN	MON.	TUES.	WED.	THURS.	FRI.
DAYS . .	A	MON (OFF)	TUES (8—4)	WED.	THURS.	FRI.	SAT.	SUN.
SPARE .	B	MON. (SHIFT) (8—4)	TUES (OFF)	WED (9—5)	THURS. (9—5)	FRI. (9—5)	—	—
NIGHTS . .	C	SAT (12—8)	SUN.	MON.	TUES.	WED.	THURS.	FRI.
EVENINGS . .	D	MON. (4—12)	TUES.	WED.	THURS	FRI.	SAT	SUN.
SPARE . .	A	MON. (SHIFT) (4—12)	TUES. (OFF)	WED (9—5)	THURS. (9—5)	FRI (9—5)	—	—
NIGHTS . .	B	SAT. (12—8)	SUN.	MON.	TUES.	WED.	THURS.	FRI.
EVENINGS . .	C	MON. (4—12)	TUES.	WED.	THURS.	FRI.	SAT.	SUN.
DAYS . . .	D	MON. (OFF)	TUES. (8—4)	WED.	THURS.	FRI.	SAT.	SUN.

Other shift cycles are also in operation.

TRACTION FEEDERS (TROLLEY 'BUS)

Week ending............................

Feeder	Line Test	Circuit Breaker Operation							Remarks
		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	
NOTTINGHAM ROAD .									
LONDON ROAD . .									
HARVEY ROAD . .									
OSMASTON ROAD WKS.									
OSMASTON ROAD SUB									
BURTON ROAD .									
NORMANTON ROAD .									
OSMASTON PARK ROAD									
ASHBOURNE ROAD .									
KEDLESTON ROAD .									
UTTOXETER ROAD .									
MARKET PLACE .									

Turbine Daily

Date..............19 .

Time	Turbine					Condensate Temps.					Oil System						
											Temps.			Pressures			
	Press.	P_1	P_2	Con. Vac.	Steam Temp.	Steam Space	Cond.	LP	HP_1	HP_2	Oil Inlet	Oil Outlet	Water Outlet	Main Pump	Bearing	Pilot	Cooler Outlet
a.m. 1.0																	
Every hour																	
Noon 12.0																	
Every hour																	
Mid-night 12.0																	

Plant Outages

Week ending.......................

Item of Plant	Outage Hours								Reason
	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.	Sun.	Total	
No. 1 T.A.									
No. 2 T.A.									
No. 1 Blr.									
No. 2 Blr.									
No. 3 Blr.									
No. 4 Blr.									
No. 5 Blr.									

N.B.—Routine maintenance turbine outages of short duration up to 12–14 hrs. for condenser cleaning, high temp. bearings, oil leaks, etc., such that set is available for day load, need not be recorded.

Log Sheet

Bearings						Air Cooling System				Circulating Water			Evaporator		Condensate Recorder	Remarks
Temperatures						Water		Air °C.					Gall.	lb.		
1	2	3	4	5	6	In	Out	In	Out	Inlet	1 Outlet	2 Outlet	Meter	Gross Output		

Oil added ... galls.
Oil drained off......galls.
Water drained off......pints.

Undertaking......................

Station..........................

Data for week ending 24.00 *Sat*..................... 19...

1. Units generated by Undertaking . . . . ______
2. Units used on auxiliaries in Station. . . . . ______
3. Units imported . . . . ______
4. Units exported . . . . ______
5. Max. demand on Turbo-Alter's over any half-hour period . . . . ______
6. Max. demand on auxiliaries at time of (5) . . . . . . ______
7. Max. demand imported during any half-hour period. . . . . ______
8. Max. demand exported during any half-hour period . . . . . ______
9. Max. demand sent to Undertaking over half-hour period . . . . ______
10. Max. demand on Turbo-Alter's at time of (9) . . . . . . ______
11. Max. demand on auxiliaries at time of (9) . . . . . . ______
12. Coal consumed in tons . . . . ______
13. Coal in stock in tons . . . . ______

Signed................................

Superintendent.

No. 1 Boiler-house Daily Log. Boiler No. .

Date......................................

	Economiser °F.				Heater °F.			Draughts Ins. W. G.				Air Pressures Ins. W.G.			Running Mills	Steam Temp. °F.	CO_2	Evaporation 1,000 lb. per hr.	Steam Pressure
	Water		Gas		Gas	Air		Furnace	Boiler Out	Econ. Out	Heater Out.	Heater		Burners					
	In	Out	In	Out	Out	In	Out					In	Out						
12 MN.																			
1 A.M.																			
2																			
3																			
4																			
5																			
6																			
7																			
8																			
9																			
10																			
11																			
12																			
1 P.M.																			
2																			
3																			
4																			
5																			
6																			
7																			
8																			
9																			
10																			
11																			
12 MN.																			

Steam Meters	Water Meters	Aux. Meters		Feed Pump	Remarks
		A.C.	D.C.		
12 MN. – 8.0 a.m.					
8.0 a.m. – 4.0 p.m.					
4.0 p.m. – 12.0 MN.					

Daily Metering Log

Date....................................

Time	Indicated Loads			Time	kW.	Printometers		RekVA. Printometers			Time	kW.	Printometers		RekVA. Printometers		
	kW.	Imprt.	Exprt.		Gen.	Exprt.	Imprt.	Gen	Exprt.	Imprt.		Gen.	Exprt.	Imprt.	Gen.	Exprt.	Imprt.
a.m. 1				a.m. 12.30							p.m. 12.30						
2				1.0							1.0						
3				1.30							1.30						
4				2.0							2.0						
5				2.30							2.30						
6				3.0							3 0						
7				3.30							3 30						
8				4 0							4.0						
9				4.30							4 30						
10				5 0							5.0						
11				5.30							5.30						
12				6.0							6.0						
p.m. 1				6.30							6 30						
2				7.0							7.0						
3				7.30							7.30						
4				8.0							8.0						
5				8.30							8.30						
6				9.0							9.0						
7				9.30							9.30						
8				10.0							10 0						
9				10.30							10.30						
10				11.0							11.0						
11				11.30							11.30						
12				Noon							12 m.n.						

MAX. IMPORT

SHIFT	k.W.	RekVA.
12–8		

MAX. IMPORT

SHIFT	k.W.	RekVA.
8–4		

MAX. IMPORT

SHIFT	k.W.	RekVA.
4–12		

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CHAPTER XXII

STATION COSTS

Capital Costs. The problem of capital cost has long been receiving the attention of engineers, and is one that has a direct bearing on the selling price of energy generated. The cost of land and buildings represents a considerable proportion of the total capital cost.

In many cases the practice of forcing down costs by severe competition has been tried, but with power station plant this usually proves as unsatisfactory for the purchasers as for the manufacturers. The policy of knowing what is wanted and what is a reasonable price to pay for it appears to give the most satisfactory results. In this way the plant in particular can be allotted to selected contractors at agreed figures. The necessity of keeping the capital cost as low as possible is often stressed, and although this is true in some respects, strictly speaking it is not quite correct to state that the capital expenditure should be kept either high or low. Each station design must be considered on its merits and full consideration given to such important factors as cost of fuel, load factor, labour charges, cost of land and buildings, etc. There is a certain capital investment which will enable electricity to be produced at the least cost for each station. The purpose of economic design is to attain the lowest production costs possible in the locality where the power station is to be built. With a high load-factor and high cost of fuel it is apparent that expenditure in plant such as feed heaters, etc., could be justified, which with low load-factor and cheap fuel would be unremunerative. Some degree of feed heating can be justified in almost all cases met with in practice. The operating efficiency of a station using coal at 45*s*. per ton should be much higher than another using coal at 30*s*. per ton, load factors being equal. If such is not the case it would appear that the design had not been based on economic principles. Low-grade fuels do not necessarily imply low production costs.

Every power station, however well designed, remains a compromise between conflicting factors and the question as to what is and what is not to be installed must still remain a matter for individual judgment. It is difficult for a manufacturer, or indeed for any

engineer who has not had to consider the design of a complete station, to realise the relative importance of the various components both from a commercial and a technical point of view. A manufacturers' opinion as to an individual piece of apparatus or section of plant is of great value, but when it comes to a question of assembling plant in a power station, other considerations than cost or the degree of efficiency of any particular item naturally step in. Having ensured reliability of operation with reasonable economy, this more than anything else is undoubtedly the criterion of success in power station design.

In one pre-war station which included some 40 acres of land, with new roads and sidings, the total cost was £901,600, or £14·1 per kW, of installed capacity. This was a low figure and was further reduced when its ultimate designed capacity was installed.

To show how the costs of a station are allocated Tables 84 and

TABLE 84. *Capital Costs of* 300 *MW Station*

Allocation	Initial Installation 150 MW £	Cost per kW. £	Completed station 300 MW £	Cost per kW. £
Site	400,000	2·66	400,000	1·33
Foundations, buildings, etc. . .	600,000	4·00	1,000,000	3·34
River works	200,000	1·33	300,000	1·00
Coal and ash handling and storage .	100,000	0·67	150,000	0·50
Turbine-house plant . . .	550,000	3·68	1,000,000	3·34
Boiler-house plant	750,000	5·00	1,300,000	4·34
Pipework	60,000	0·40	110,000	0·36
Switchgear, transformers and cables .	180,000	1·20	340,000	1·13
Lighting, tools, furniture, etc. . .	10,000	0·06	13,000	0·04
	2,850,000	19·00	4,613,000	15·38
Engineering and contingencies . .	171,000	1·14	277,000	0·92
	3,021,000	20·14	4,890,000	16·30
Interest on capital during construction	196,000	1·31	318,000	1·06
Total cost . . .	3,217,000	21·45	5,208,000	17·36

85 have been compiled and may be taken as typical of pre-war high-capacity stations.

The economic limits of the various items are now generally accepted at :—

Land	60 years
Substantial buildings	30 ,,
Plant	20 ,,

The figures are given for the purpose of comparison only and do not refer to any particular station. It will be observed that the total cost is at the rate of £21·45 per kW. installed in the first section and £17·36 in the completed station.

The leading particulars of the plant installed in Table 84 are as follows :—

50 MW 1,500 r.p.m. turbo-alternators.
260 k.p.h. stoker-fired boilers.
Boiler pressure : 625 p.s.i., 850° F.
Final feed temperature : 350° F. (5 stages).
Condenser conditions : N.E.R. 29″ Hg.–30″ Baro.
London Area 1930–36.

TABLE 85. *Capital Costs of 240 MW Station*

Item	Generation		Distribution	
	Total Cost £	Cost per kW. £	Total Cost £	Cost per kW. £
Land	24,000	0·100	—	—
Buildings and civil works . .	580,000	2·420	70,000	0·292
Turbo-alternators and condensing plant	800,000	3·330	—	—
Cooling towers, etc..	405,000	1·685	—	—
House sets, works transformers, battery, etc.	55,000	0·230	—	—
Boilers and auxiliary plant . .	1,070,000	4·460	—	—
Coal and ash-handling plants, and sidings	330,000	1·370	—	—
Pipework—steam, feed and cir. water	78,000	0·325	—	—
Switchgear	195,000	0·815	117,000	0·488
Main transformers	—	—	130,000	0·542
Main cables	100,000	0·417	—	—
Workshops	18,000	0·075	—	—
Wiring and lighting	19,000	0·080	—	—
Miscellaneous	3,000	0·013	2,000	0·008
Total cost	3,677,000	15·320	319,000	1·330

The particulars of the plant given in this table are :—

3/30 MW and 3/50 MW.
3,000 and 1,500 r.p.m. turbo-alternators.
Stoker and pulverised fuel boilers.
375 p.s.i. and 620 p.s.i.
280/340° F. final feed (3 stages).
28·4/28″ Hg (30″ Baro) N.E.R.
Provincial area, 1930/38.

Table 86 shows how the costs vary for each plant extension for one provincial power station.

The typical station given in Table 84 is taken as an example to illustrate the method of computing the capital charges per unit. Taking 5 per cent. as the rate for simple interest on capital, and compound interest on sinking funds, the following multipliers are taken from the usual table of sinking funds.

60 years life—multiplier—	0·002828	(*a*)
30 ,, ,, ,,	0·015050	(*b*)
20 ,, ,, ,,	0·030240	(*c*)

The capital costs of the 300 MW station are :—

	£	£ per kW.
(*a*) Land	400,000	1·33
(*b*) Buildings and river works . .	1,300,000	4·34
(*c*) Plant	2,913,000	9·71
	4,613,000	15·38

Annual Capital Charges are :—

Interest 5 per cent. on £4,613,000	£231,000
Sinking funds at 5 per cent. on—	
Land—£400,000 × 0·002828	1,130
Buildings—£1,300,000 × 0·01505	19,500
Plant—£2,913,000 × 0·03024	88,500
	£339,130

To obtain the capital charge per unit the total capital charges per annum will have to be divided by the annual output in units. It will be appreciated that the capital charge per unit will depend upon the load factor of the station and for the purpose of illustrating this point three load factors are taken.

		Capital charges pence per unit
25 per cent. load factor	(657,000,000 units per annum) .	0·1200
50 ,, ,, ,,	(1,314,000,000 ,, ,, ,,) .	0·0600
100 ,, ,, ,,	(2,628,000,000 ,, ,, ,,) .	0·0300

TABLE 86. *Power Station Capital Costs*

Year ordered	1928	1933	1935	1936	1937	Remarks
Section of work	1–30 MW 3–188 k.p.h.	1–30 MW 3–188 k.p.h.	1–30 MW *2–188 k.p.h.	1–50 MW *1–188 k.p.h.	1–50 MW *3–188 k.p.h.	Total 190 MW. (£2,469,920, excluding land).
	£	£	£	£	£	
Buildings	171,530	24,260	150,850	21,200	76,200	*Steam.* 625 p.s.i., 850° F.
Turbo-alternator plant	88,210	98,250	106,000	180,000	203,000	*Feed.* 250° F. 3 Stages N.E.R.
Boiler plant	156,450	227,190	170,000	81,250	263,000	*Vacuum.* 28·25″ Hg. N.E.R.
Coal and ash handling	37,540	3,500	46,800	10,800	20,400	Three reinforced concrete cooling towers, prices of which are spread over periods.
Circulating water system	5,000	1,450	2,000	10,000	9,600	Two boiler houses at right angles to turbine house.
Cooling towers	19,200	13,380	14,000	14,000	36,000	Six chain grate stokers (*a*).
Switchgear	55,100	14,660	53,500	13,600	21,000	Six retort stokers (*b*).* Plate-type air heaters on (*a*).
General electrical works, etc.	7,000	10,000	10,000	7,000	17,000	Rotary type air heaters on (*b*). One steel chimney per boiler. Twin condensers.
Total	540,030	392,690	553,150	337,850	646,200	Step-up transformers on 50 MW sets, 11/33 kV. One inter-bus transformer.
Cost per kW.	18·0	13·0	18·4	6·8	12·9	Turbo-alternators 11 kV., 1,500 and 3,000 r.p.m. One steam shunting loco. Skip hoists and belt conveyors. Ash sluicing system. Metalclad indoor switchgear.

To show the relative importance of capital and operating costs with various load factors, Fig. 546 is included. The figures given have been taken at random and should not be used as a basis of

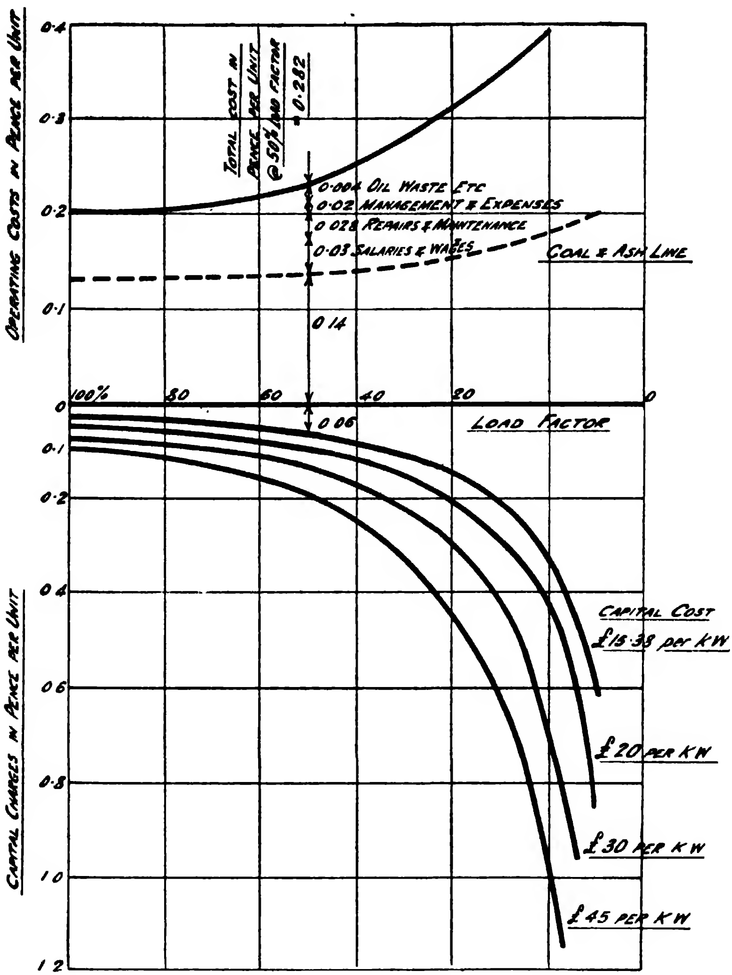

FIG. 546. Curves showing relative importance of Capital and Operating Costs with various Load Factors.

any calculations without first considering all aspects of the question under review.

Table 87 gives the percentage sinking fund deposit (annual periods) for finding annual cost.

The annual deposit to realise £1 in the stated number of years (figures in £'s per annum). The deposit is assumed to be made at the end of each year and interest is compounded annually.

TABLE 87. *Multipliers for Sinking Funds*

Years.	Interest		
	4 per cent.	5 per cent.	6 per cent.
1	1	1	1
5	0·1846	0·1810	0·1774
10	0·0833	0·0795	0·0759
15	0·0499	0·0463	0·0430
20	0·0336	0·0302	0·0272

In view of the fact that capital costs are now some 200 to 300 per cent. higher than pre-war figures it is probably better to itemise costs on a percentage basis as follows :—

	Percentage of Total
Site	8·0
Foundations and Buildings	22·0
River works	7·0
Coal and ash handling plants	3·0
Turbine house plant	21·0
Boiler house plant	27·0
Pipework	2·5
Switchgear, Transformers and cables	8·0
Lighting, tools and furniture	0·5
Engineering contingencies	1·0
Total	100·0

Cooling towers . . . . . 12 per cent. approx.
Cost per KW on present-day basis £50–60

Summary :

Plant	63 per cent.
Land, buildings and Civil Engineering works	37 per cent.
Total	100 per cent.

Operating Costs. It is difficult to obtain reliable figures upon which comparison may be made in all sections of the station, and those chosen in the examples given do not refer to any particular plant.

The operating costs may be sub-divided into the following sections :—

	Average works Cost per Unit sent out Pence.
Fuel including transport	0·427
Fuel handling, etc.	0·023
Operation salaries and wages	0·033
Oil, water and stores	0·003
Repairs and maintenance	0·041
Total	0·527 pence

The most important item so far as the operation side is concerned is the cost of coal, and every effort should be made to conserve it. It will be observed from Table 1, Volume I., that the coal consumption is now below 1 lb. per unit generated. The following example shows how the capital and operating costs affect the price per unit output.

Station capacity . . . 100 MW.
Capital cost . . . £15 per kW.
Annual charges . . . 8 per cent.
Cost of fuel . . . 15*s*. per ton.
Fuel consumption . . 1·5 lb. per unit generated.
Operating costs, to include fuel costs plus 20 per cent. of the wages, salaries and repairs.
Salaries, wages and repairs . £40,000.

(*a*) 60 MW. maximum demand, load factor 30 per cent.
(*b*) ,, ,, ,, ,, ,, 50 ,,

(*a*) Fixed Costs.

Total station cost = £15 × 100,000 = £1,500,000
Annual charges at 8 per cent. × £1,500,000 = £120,000
80 per cent. salaries, wages and repairs = 0·8 × £40,000 = £32,000

£152,000

$$\text{Fixed charge per kW. demand} = \frac{152,000}{60,000} = £2{\cdot}54.$$

Operating Costs.

20 per cent. salaries, wages and repairs = 0·2 × £40,000 = £8,000

$$\text{Or per unit} = \frac{8,000 \times 240}{8,760 \times 60,000 \times 0{\cdot}3} = 0{\cdot}012d.$$

$$\text{Fuel cost per unit} = \frac{1{\cdot}5 \times 15 \times 12}{2,240} = 0{\cdot}120d.$$

$$\text{Total operating cost} = 0{\cdot}132d.$$

$$\text{Fixed charge per unit} = \frac{152{,}000}{8{,}000} \times 0{\cdot}012 = 0{\cdot}227d.$$

$$\therefore \text{ Total cost per unit output} = 0{\cdot}132 + 0{\cdot}227$$
$$= \underline{0{\cdot}359} \text{ pence.}$$

(*b*) Fixed Costs.
This will be same as in (*a*), *i.e.*, £2·54 per kW.

Operating Costs.

$$\text{20 per cent. salaries, wages and repairs} = 0{\cdot}2 \times £40{,}000 = £8{,}000$$

$$\text{Or per unit} = \frac{8{,}000 \times 240}{8{,}760 \times 60{,}000 \times 0{\cdot}5} = 0{\cdot}007d.$$

$$\text{Fuel cost per unit} = (\text{as in } (a)) = 0{\cdot}120d.$$

$$\text{Total operating cost} = \underline{0{\cdot}127d.}$$

$$\text{Fixed charge per unit } \frac{152{,}000}{8{,}000} \times 0{\cdot}007 = 0{\cdot}133d.$$

$$\therefore \text{ Total cost per unit output} = 0{\cdot}127 + 0{\cdot}133$$
$$= \underline{\underline{0{\cdot}26}} \text{ pence.}$$

It will be appreciated that the figures given in this example do not represent present-day practice but the general application is the same.

In ascertaining the generation fixed charges and running charges components of a tariff it is sometimes necessary to sub-divide as indicated in Table 88. It will be noted that such items as coal,

TABLE 88. *Generation Costs*

	Generation	
	Fixed Costs "F"	Running Costs "R"
Coal	£7,000	£48,000
Oil, water and stores	80	400
Salaries and wages	9,000	1,900
Repairs and maintenance	6,020	300
	22,100	50,600
Management expenses	10,000	—
Rents, rates and taxes	20,000	—
Capital	90,000	—
Total	£142,100	£50,600

water, oil, repairs and maintenance, wages, etc., appear under both fixed and running charges for it is not strictly correct to effect a straight allocation of these items into any one group. The reasons for this are broadly :—

(1) Coal costs are partly chargeable to fixed costs in the form of banking and standby losses, although this would not be so in the case of pulverised fuel boiler plant. A certain amount of coal and oil are, however, still required for lighting up, etc.

(2) The greater proportion of repairs and maintenance costs, salaries and wages can be allocated to fixed charges.

(3) Interest, depreciation and certain other overhead charges which are usually paid out of the gross profit of the undertaking are usually divided between the fixed and running costs in proportions representative of the earning capacity of these two sections of the undertaking.

$$\begin{aligned}\text{Generation Fixed Charges component} &= \frac{\text{Total fixed costs}}{\text{Maximum demand} \times \text{diversity factor}} \\ &= \frac{142{,}100}{30{,}000 \times 1{\cdot}1} \\ &= £4{\cdot}3 \text{ per kW.}\end{aligned}$$

This assumes a diversity factor of 1·1 for bulk consumers supplied direct from station bus-bars and a maximum demand of 30,000 kW.

$$\begin{aligned}\text{Generation Running Charges component} &= \frac{\text{Total running costs}}{\text{Total units sent out}} \\ &= \frac{50{,}600 \times 240}{100{,}000{,}000} \\ &= 0{\cdot}122 \text{ pence per unit (kWh).}\end{aligned}$$

This assumes 100,000,000 units sent out per annum.

Some present-day costs for a 250 MW station may prove of interest, but each station must be considered on its own.

Capital cost	£11,125,000
Annual cost of salaries and wages	£80,000/100,000
Annual cost of repairs and maintenance, including oil, water, stores, etc.	£150,000/200,000
Management charges, excluding rates, interest, sinking fund, etc.	£15,000/25,000
Total personnel employed	300/400

A comparison between an oil and coal burning station (1949 basis) with 40 per cent. load factor shows that the cost of production would be higher in the case of oil :

0·76 pence/unit generated	oil
0·69 pence/unit generated	coal

Some idea of the operation and maintenance costs of a steam power station will be obtained from Tables 89 and 90 which refer to a station having the following plant at March 31st, 1945 :—

2—15 MW., 200 p.s.i. turbo-alternators.
1—20 " " " "
1—30 " " " "
1—30 M.W., 650 p.s.i. turbo-alternators. (In commission part 1942. Out for four months, 1944).
1—2·5 " 1,000 " "
3—200,000 lb./hr., 650 p.s.i. Retort Stoker Boilers with reducing values to 200 p.s.i.
4—Retort Stoker Boilers } Average rating 60,000 lb./hr.
3—Chain Grate Stoker Boilers } approx.
5·35 m.g.p.h. Wood Cooling Towers.

Fig. 547 shows typical steam production costs.

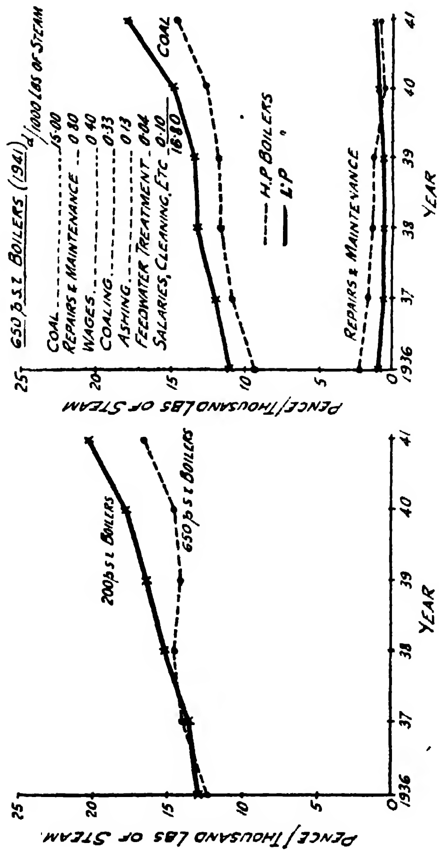

Fig. 547. Cost of Steam Production.

TABLE 89. *Generation Works Costs*

Calendar Years	1936	1937	1938	1939	1940	1941	1942	1943	1944
Units sent out	190,108,190	203,181,720	179,824,820	165,383,530	195,655,900	218,755,170	233,423,770	266,090,240	264,525,090
					Operation				
	£	£	£	£	£	£	£	£	£
Fuel Costs :—									
Coal and Coke	100,724	122,286	119,387	117,570	159,720	204,507	245,579	278,141	338,177
Handling Charges :—									
Coal and Coke	1,654	1,826	1,902	2,300	5,244	4,376	4,387	7,112	9,627
Ash	846	1,298	1,185	1,307	1,735	2,142	4,059	6,214	5,771
Sales :—									
Ashes	278	517	430	382	517	484	531	496	447
Steam			44	90	108	126		152	182
Total Fuel	102,946	124,893	122,000	120,705	166,074	210,415	253,494	290,819	352,946
Oil and Stores	420	442	630	677	851	991	1,296	1,233	1,300
Water—Town and Well	7,940	8,478	7,936	7,308	9,204	9,985	11,011	10,025	11,098
Salaries and Wages :—									
Boiler House	6,420	6,780	5,515	4,698	6,328	7,132	8,127	8,600	9,448
Turbine House	3,023	3,044	3,107	3,326	3,966	4,891	5,276	6,655	6,710
Ordinary	2,599	2,278	2,658	3,068	3,413	3,815	4,290	5,227	5,035
Salaries	4,484	4,607	5,570	5,886	6,565	6,495	6,510	6,046	7,222
Total Salaries and Wages	16,526	16,709	16,850	16,978	20,272	22,333	24,203	26,528	28,415
Total Operation Costs	127,832	150,522	147,416	145,668	196,401	243,724	290,004	328,605	393,759
Cost/U.S.O.	·161	·178	197	·211	·241	·267	·298	·296	·357
					Repairs and Maintenance				
Coal Handling	1,802	1,774	2,238	858	2,117	2,238	3,495	4,585	2,752
Ash Handling	3,337	3,295	2,390	1,477	2,771	2,273	3.030	4,582	3,005
Boilers	14,225	13,328	12,670	9,861	11.286	13.799	19,805	24,058	29,153
Turbines	1,612	1,986	852	1.556	1,385	17,591	2,661	2,312	3,776
Other Mechanical Plant	2,501	3.932	4,644	3,906	3,357	4,152	4,088	5,182	4,818
Alternators	103	366	90	216	154	430	700	416	422
Other Electrical Plant	3,852	3,703	3,940	4,344	4,730	3,910	5,969	6,376	7,145
Buildings	2,751	4,092	4,014	4,216	3.275	3,912	6,826	9,178	8,544
Circulating Water Plant and Cooling Towers	574	209	2,831	324	2,046	606	1,163	1,920	1,983
Salaries—General								1,418	995
Total Repairs and Maintenance	30,757	32.685	33,669	26,758	31,121	48,911	47,737	60,027	62,359
Cost/U.S O.	·039	·038	·045	·039	·038	·054	·049	·054	·057
Grand Total	158,589	183,207	181,085	172,426	227,522	292,635	337,741	388,632	456,352
Total Cost/U S O.	·200	216	·242	·250	·279	·321	·347	·350	·414

Table 90. *Cost of Production and General Data*

	1936	1937	1938	1939	1940	1941	1942	1943	1944
Fuel Consumed (tons)									
Coal	143,773	153,148	128,962	122,282	147,819	165,549	180,959	189,110	200,882
Coke					3,311	1,625	293	52	—
Total	143,773	153,148	128,962	122,282	151,130	167,174	181,252	189,162	200,832
Fuel Cost :—	£	£	£	£	£	£	£	£	£
Coal	100,724	122,286	119,387	117,570	157,604	203,599	245,413	278,112	338,177
Coke					2,116	908	166	29	—
Total	100,724	122,286	119,387	117,570	159,720	204,507	245,579	278,141	338,177
Handling and Storage :—									
Fuel	3,456	3,600	4,140	3,155	7,361	6,614	7,882	11,697	12,379
Ash	4,183	4,593	3,575	2,784	4,506	4,415	7,089	10,796	8,776
Sale of Ash	278	517	430	382	517	484	531	496	447
Sale of Steam			44	90	108	126		152	182
Total Fuel	108,085	129,962	126,628	123,040	170,962	214,926	260,019	299,986	358,703
Oil and Stores	420	442	630	677	851	991	1,296	1,233	1,300
Water :—									
Town	7,940	8,478	7,936	7,308	9,204	9,985	11,011	9,304	10,328
Well								721	770
Salaries and Wages :—									
Operation	16,526	16,709	16,850	16,978	20,272	22,333	24,203	26,528	28,415
Repairs and Maintenance :—									
Boilers	14,225	13,328	12,670	9,861	11,286	13,799	19,305	24,058	29,153
Turbines	1,612	1,986	852	1,556	1,385	17,591	2,661	2,312	3,776
Other Mechanical Plant	2,501	3,932	4,644	3,906	3,357	4,152	4,088	5,182	4,818
Alternators	103	366	90	216	154	430	700	416	422
Other Electrical Plant	3,852	3,704	3,940	4,344	4,730	3,910	5,969	6,376	7,145
Buildings	2,751	4,092	4,014	4,216	3,275	3,912	6,826	9,178	8,544
Circulating Water Plant and Cooling Towers	574	209	2,831	324	2,046	606	1,163	1,920	1,983
Salaries, General								1,418	995
Total Repairs and Maintenance	25,618	27,616	29,041	24,423	26,233	44,400	41,212	50,860	56,836
Total Works Costs	158,589	183,207	181,085	172,426	227,522	292,635	337,741	388,632	456,352
	(·200)	(·216)	(·242)	(·250)	(·279)	(·321)	(·347)	(·350)	(·414)
Overhead Charges	131,677	122,975	118,283	124,038	155,557	152,030	150,597	147,307	158,163
	(·166)	(·146)	(·158)	(·180)	(·191)	(·167)	(·155)	(·133)	(·144)
Total Cost of Production	290,266	306,182	299,368	296,464	383,079	444,665	488,338	535,939	614,515
Cost/U.S.O.	·366	·362	·400	·430	·470	·488	·502	·483	·558

Units—Millions									
1. Generated	206·22	219·22	195·09	180 22	214·73	239·72	254·98	288·54	288·57
2. Used on Works	16 11	16 04	15·27	14·83	19·07	20·96	21·55	22·45	24·04
3. Per cent. used on Works, *i e.*, $\frac{\text{Units used on Wks.} \times 100}{\text{Units generated}}$	7·81%	7·32%	7·83%	8 28%	8·88%	8 75%	8·45%	7·78%	8 33%
4. Electricity Board									
(*a*) Exported to	32·24	38 62	24·53	5 45	13·64	32 48	26·10	50 60	41·2
(*b*) Imported from	4·94	15·55	29·76	35·25	33·18	43 10	27·41	13 73	16·36
5. Sent out									
(*a*) From Generators 1 − 2	190 11	203·18	179·82	165·39	195·66	218·76	233·43	266·09	264·53
(*b*) To Undertaking 5*a* + 4*b* − 4*a*	162 81	180·11	185 06	195·19	215·20	229 38	234·73	229·22	239·62
6. kW. Maximum Demand									
(*a*) On Generators	56,150	68,770	60.880	61,420	68,640	72,320	78,170	73,750	82,190
(*b*) Sent out	52,290	64,320	56,790	57,390	63,310	67,000	72,780	68,830	76,610
7. kW. Average Load, *i.e.*, $\frac{\text{Units Generated}}{\text{Hours Run}}$	24,215	23,616	23.539	26.467	30,535	29,231	33,718	36,104	35,072
8. Load Factor, *i.e.*, $\frac{\text{Units Generated} \times 100}{\text{Total M.D.} \times \text{Hrs. Run}}$	43·13	41·61	46·88	43·09	44·49	40·42	43·13	48·95	42·68
9. Plant Factor, *i.e.*, $\frac{\text{Units Generated}}{\text{Sum (M.C.R} \times \text{Running Hrs.)}}$	60·08	66·92	66·67	64·10	72·92	71 79	75·91	71 02	72·78
10. Installed Capacity kW.	102,000	88,500	88,500	88,500	88,500	88,500	118,500	118,500	118,500
11. Coal—lb. per unit sent out	1·694	1·688	1·606	1·656	1·73	1·712	1·739	1·592	1·701
12. B.Th.U.'s per lb. of Coal	11,930	11,890	12.310	12,240	12,020	12,100	12,050	11,735	11,772
13. ,, per unit sent out	20,210	20,075	19,775	20,272	20,797	20,713	20.959	18,687	20,021
14. Thermal efficiency per unit sent out	16 88	17·00	17·25	16·83	16·41	16·47	16·28	18·26	17·05
15. Average cost per ton of fuel consumed	14/0·138	15/11·636	18/6·181	19/2·752	20/10·58	24/5·48	27/1·18	29/4·89	33/8·13
16. Staff—Operation	12	12	12	12	14	12	11	10	13
17. ,, Maintenance	3	3	3	3	3	3	3	2	4
18. ,, Clerical and Stores	7	7	7	7	7	7	7	7	7
19. Men—Operation	76	78	75	74	86	86	99	114	110
20. ,, Maintenance	73	75	70	54	53	59	66	90	116

Transmission Costs. It is difficult to obtain reliable data for such costs and the following refer only to one undertaking :—

Annual charge per kVA of feeder capacity . . .	5*s*.
Cost of losses per unit (kWh) transmitted . . .	0·0094*d*.

These costs are based on a 15 MVA feeder operating at 30 per cent. load factor and include for the necessary transformer at each end.

Diversity Factor. Is the ratio of the sum of the maximum loads of the individual consumers supplied during a given period, to the maximum load during the same period; or is the ratio of the sum of the maximum demands of part of a system to the maximum demand of the whole system.

Depreciation Allowance. Is the sum of money which should be put aside to replace plant, buildings, etc., when worn out or to form a fund from which new plant, etc., may be purchased to replace the old without drawing on capital.

Obsolescence. Is the taking into account the possibility of replacement of plant, etc., before it is worn out.

Original Value. For purposes of depreciation this value should include the purchase price, transport charges, foundations and fixing, and cost of all incidental accessories.

Plant. The depreciation of plant is dealt with by assigning to each section of plant a given number of years' useful life after taking into account the probability of obsolescence.

Buildings. The probability of obsolescence does not arise with buildings, and it is unlikely that a building would require to be replaced during its normal period of life, except for natural decay. The rate of depreciation to be allowed on buildings depends on the stability and durability of the structure, whether permanent or temporary, and the conditions of the owners' occupation, whether freehold or leasehold. The nature of the site will also be taken into consideration.

Methods of Allowance for Depreciation

(1) Straight line law (same contribution, set aside each year).

$$D = \left(\frac{O - R}{n}\right) \text{ £}_s \text{ per annum.}$$

(2) Interest law (investing depreciation fund).

$$D = \frac{r\,(O - R)}{(1 + r)^n - 1} \text{ £}_s \text{ per annum.}$$

(3) Constant percentage of a reducing value (heavily in early life and less in later life).

D = k.O for first year.

D = k (O − k.O) second year and so on.

$$k = 1 - \sqrt[n]{\frac{R}{O}}$$

Where D = depreciation contribution per annum £$_s$.

O = original value of plant or buildings, etc., in £$_s$.

R = residual value of plant or buildings at end of "n" years in £$_s$.

n = probable duration of useful life in years.

r = interest on £1 per annum, *i.e.*, $\frac{r \text{ per cent.}}{100}$

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CHAPTER XXIII

FIRE-FIGHTING AND AIR RAID PRECAUTIONS

THROUGHOUT the book reference has been made to the design, layout and arrangement of various items of plant and buildings to ensure a reasonable degree of fire protection. The nature of the fire risk associated with power station plant and in particular the electrical plant differs from that associated with other materials. The difference arises on account of the high degree of inflammability of some of the materials used in electrical apparatus.

In all cases of outbreak of fire the following factors play a part :—

(1) Site of the fire.
(2) The degree of inflammability of the materials.
(3) The time which elapses before the fire can be effectively dealt with.
(4) The methods which can be safely adopted to fight the fire and the suitability of such methods employed to attack the fire.

The site of electrical apparatus may be such that an outbreak of fire may give rise to serious danger and the importance of the installation and maintenance of an efficient fire-fighting system has been realised. In the first place large quantities of oil are permanently stored throughout various sections of the buildings. Items of prime importance are the insulating oils necessary for switchgear, transformers, reactors and possibly cables and also lubricating oils for the turbo-alternators and auxiliary plant. The use of the central system for pulverised fuel plants also demands special consideration.

Some idea of the quantities of oil involved will be gathered from the following :—

1,500 MVA., 33 kV. switchgear . .	1,000 gallons of oil per three-phase equipment.
40 MVA. transformer . . .	9,500 gallons.
50 MW turbo-alternator . . .	3,500 „

Systematic sectionalising and sub-division of plant and buildings wherever site conditions permit are essentials of any fire protection scheme. In carrying out these principles it is necessary to bear in mind :—

(1) Prevention of fire.
(2) Control of fire and prevention of damage to healthy plant.
(3) Methods of fire-fighting to be employed.

The prevention of fire depends primarily on the design, construction, materials and protective devices employed for the individual items of plant. The limitation of the extent of fire will be greatly helped by physical separation of important sections of plant. At the present time the methods and equipment of fire-fighting are many and varied, but no doubt as more experience is gained certain standards will be laid down and followed.

Fires can be extinguished according to two fundamental principles :—

(1) Reducing the temperature below ignition point.
(2) Preventing access of air.

The detection of fires is another important point, the two chief methods used being heat detection and smoke detection.

Hand equipment is usually provided, and, if this is to be of use, extinguishers should be available both inside and outside the building. There are various types : soda acid, carbon tetra-chloride, methyl bromide, chemical foam and carbon dioxide. Soda acid is not very suitable for fires of electrical origin but for certain inflammable stores and packing material it is ideal. The others are in

TABLE 91. *Comparative Costs of Automatic Fire-fighting Equipment.*

Switch House "A"—50,000 cubic ft.; Brick Building.
Cable Basement, "B," 6,400 cubic feet.
Cable Basement, "C," 3,400 cubic feet.

Section Protected	Gas		Water	Remarks
	Carbon Dioxide	Methyl Bromide	Sprinkler	
Protection of switchroom "A" and basement "B" by total flooding.	1·0	1·18	0·5	Includes all builder's work, etc.
Individual flooding. Separate protection of switchroom "A" and basement "B" and "C"	1·0	1·2	0·48	,,
Protection of switchroom "A" only.	1·0	1·14	0·5	,,
High-pressure pumping plant and other auxiliaries.	—	—	0·75	,, This must be added to the sprinkler cost in each case.

general suitable for oil-insulation fires and manufacturers are always willing to give instructions regarding their uses, etc.

Fixed installations are of two main types, gas or fluid. In the first there is a choice between CO_2 and methyl bromide ; in the latter, water or mechanical foam. Before making a decision it is desirable to consider a number of factors :—safety to life and plant, reliability, maintenance, initial cost, space required and the adaptability to existing and new buildings and plant. Typical comparative costs for switch-house fully automatic fire-fighting equipments are given in Table 91, although each installation will have to be considered on its merits.

Inert gases have the advantage of extinguishing a fire almost immediately it breaks out without causing considerable damage and dislocation, as is often the case with water. In the systems employing water it is contended that a film of oil and water emulsion is spread over the entire surface which excludes all air and puts out the fire. Extinction of fires in a confined space consists of total flooding of the space with sufficient gas to render the atmosphere inert and non-supporting to combustion and also to provide an excess of gas to allow for leakages. Extra gas is provided to give a reasonable factor of safety to ensure complete and permanent extinction. An atmosphere containing 17 per cent. CO_2 is inert ; the usual practice for fire extinguishing purposes is to provide sufficient gas stored in liquefied form in cylinders to give 50 per cent. concentration in the volume to be dealt with. As a guide 5 to 8 lb. of CO_2 is required for 100 cubic ft. volume of air space. Cylinders of gas holding 28 to 80 lb. can be obtained. To test for leakage a cylinder is weighed. CO_2 has a 17 per cent. higher dielectric strength than air.

For all usual electrical and turbine oil fires it appears that ordinary hose, fitted with special diffuser-nozzles, would deal effectively with such outbreaks and further are comparatively cheap.

Switch-house equipment usually consists of a gas-flooding installation employing either carbon dioxide or methyl bromide, the equipment being arranged to give automatic indication on a control panel of any fire. Many engineers favour CO_2. The discharge of the gas cylinders is remote electrically operated from the control panel. Manual operation from the main banks of cylinders is also provided. Switchgear fires are often preceded by an explosion, in which case the windows of the building would no doubt be blown out and the equipment should be designed to cope with these conditions. An extraction fan may be provided in each switch-house to clear the chamber of smoke and fumes as quickly as possible after a fire has

been extinguished. In a very short space of time after the commencement of a fault the smoke produced may be so dense that it is impossible to see the lights by which the room is illuminated. Further, this smoke may be of so acrid a nature that for a considerable period the switch chamber cannot be entered to ascertain the extent of the damage and make such adjustments as may be necessary to restore the supply to the circuits which have been automatically cut-off or deranged. Relays are placed at suitable positions in the various switch houses or sections thereof to ensure that in the event of an outbreak of fire the minimum delay shall elapse before the operation of the alarm system. Suitable signs are placed warning occupants of protected areas and the necessity for immediate exit. All gang-ways and corridors should be free from obstruction.

For the protection of transformers, reactor banks and cable tunnels, high-pressure water spray equipment is often used. This is usually fully automatic, but manual operation is available a safe distance from the hazard. The indication system and precautions adopted for switch-house protection also apply.

A trained fire-fighting staff should be maintained at all power stations. The equipments usually required by such a staff are: protective clothing, helmets, gas masks, hoses, stand-pipes, hydrant keys, breechings, branch pipes and a portable pump. A good water supply is essential and use may be made of river, canal or cooling-tower water if a pump is available. The use of the static head and water available in large towers is also possible and was referred to in Chapter IV, Volume I. Much time can be saved in engaging an outbreak of fire if a dry main is installed throughout the most important buildings and plant. The main can be charged by either fixed or portable pumps. Steam and petrol pumps are preferable although stand-by electric pumps may be very useful at such times. A landing valve may be placed on each floor of the boiler, turbine and switch-houses and also at any other vulnerable point in the station. Each supply point may have a cradle carrying a length of hose with branch fixed ready for use. Buckets of sand placed in readily accessible positions are useful for outbreaks of local fires.

Water systems are apparently most suitable for outdoor switchgear and transformer layouts and the gas systems preferable for indoor installations. As a fire should be dealt with at once it appears essential that automatic apparatus be used, for non-automatic apparatus depends on the human element and errors

may be introduced. In regard to water systems the following deserve consideration : (1) Water pressure. (2) Quantity of water available. (3) Atmospheric temperature conditions.

Water pressure may be augmented by pumps or, alternatively, by water stored in tanks under air-pressure. To prevent frost affecting the equipment during very cold weather the detector piping system is charged with air at a pressure of about 25 p.s.i.

(Also see Independent House Service Alternators).

TABLE 92. *Minimum Distance between the Nozzle and the Live Conductors*

Voltage to Earth of Live Conductors.	Diameter of Nozzle Orifice and distance.		
	(0·28 in.) yds.	(0·71 in.) yds.	(1·20 in.) yds.
110 A.C. . . .	0·55	1·08	2·18
450 D.C. . . .	0·82	3·28	5·47
3,000 A.C. . . .	2·18	5·47	10·80
6,000 ,, . . .	2·74	6·55	13·10
12,000 ,, . . .	3·28	7·10	16·40
60,000 ,, . . .	4·90	13·10	24·00
150,000 ,, . . .	6·55	16·40	27·40

Remarks :

(*a*) The figures are for water with a resistivity of about 3,000 ohms per cubic centimetre, but water as low as 2,000 ohms per cubic centimetre is possible.

The figures would have to be adjusted in accordance with the water supply available.

(*b*) The figures will not apply when water is directed downwards in a vertical or almost vertical direction.

Water directed by hose (without diffuser-nozzle) on to burning oil is liable to cause explosions and impede the progress of firemen. The ordinary hose operating from the fire main and fitted with a diffuser-nozzle is useful and is cheap. The diffuser-nozzle projects water in the form of a hollow cylinder, thus reducing the cross-section of the water to a low figure. On attacking a fierce fire, the diffuser-nozzle is first adjusted to project a parallel hollow jet of

water so that the fire may be fought from a safe and probably more comfortable distance, the water being used with the object of reducing the temperature at the seat of the fire. As the fire is overcome so the diffuser-nozzle is adjusted to spray water out into the form of an umbrella and the fireman can then approach very close to the fire. He can then direct the umbrella of water immediately over the seat of the fire and smother it. It can be applied without the need for making the plant "dead" and is suitable for dealing with auxiliary switchgear, transformers, turbine oil and boiler fuel oil fires, etc. Some idea of the distances at which men can work with safety on live apparatus will be noted from Table 92.

At many important substations fixed automatic fire extinction apparatus is placed within the blast walls or other surrounds. Taking into account the possibility of derangement of fixed apparatus and the degree of protection required it is usually advisable to provide hydrants for "back-up" purposes. Where automatic water systems are installed for indoor plant an external coupling should be included to enable the fire brigade to make a hose connection and thus deal with the fire from outside the building. The idea is to augment the supply of water should the pressure drop before the fire is subdued. In some undertakings all high voltage consumers' substations are periodically visited by representatives of the local fire brigade, who attach their own identification plate. Every high-voltage consumer has a key for access to the sub-station. Officers of the fire brigade receive instructions in the opening of high voltage circuit-breakers to be able to open them immediately on arrival at consumers' premises.

The following are typical working instructions for 132 kV. working when washing insulators :—

(1) The length of water jet to be not less than 20 ft.

(2) Jet to be broken up into a spray before coming into contact with the line insulator.

(3) The specific resistance of water to be not less than 2,000 ohms./cm.[3]

(4) The nozzle of the hose to be efficiently earthed by means of duplicate conductors of adequate cross-section.

The principles to be followed may be broadly summarised as follows :—

(1) Segregation and separation of duplicate items of apparatus and plant wherever possible.

(2) Insistence on sound design and construction of the installation since prevention is better than cure.

(3) Rapid interruption of the supply to the faulty plant. This necessitates complete protection of the tripping circuits throughout their routes.

(4) Limitation of oil spreading by adequate wells or sumps and provision of effective drainage areas close to the plant protected.

(5) Provision of proper facilities for fire fighting, adequate reserve water supplies and free access to all vulnerable positions on the site.

(6) The facilities to organise and maintain at a high standard a station fire-fighting unit drawn from the staff and employees.

The problem of dealing with oil tank fires in turbine house basements has been met by providing a 6 to 8 in. pipe at each vulnerable point and taking it outside. By this means it is possible to inject "foam" or other fire-fighting medium without entering the basement.

Air Raid Precautions. Reference has already been made to the design and construction of buildings to guard against blast and splinters. Air raid precautions may be summarised as follows :—(1) Protection of operating and other staffs. (2) Protection of plant. (3) Protection of buildings. (4) Provision of special lighting. (5) Special means of communication with the various buildings and also the local A.R.P. and fire brigades.

The protection of operatives, plant and buildings against blast, splinters, small incendiary and fire bombs or gas bombs will have to be undertaken. The protection of staff is the most essential, though the degree of protection possible may be far from that desired as site conditions sometimes prohibit the provision of suitable accommodation. Each station must be given individual consideration, Both inside and outside shelters will be necessary and in the majority of cases these will be designed to withstand the impact of large masses of falling brickwork, etc. The operating personnel will remain at their posts during an air raid and suitable steel or reinforced concrete shelters will be required. Properly constructed underground shelters or reinforced concrete shelters with steel linings are probably the most satisfactory. Protective clothing and fire-fighting apparatus is also necessary and should be placed in accessible positions throughout the station.

The protection of plant is a problem demanding considerable thought because of its widely varying nature and the layouts adopted.

Although complete destruction is usually confined to a compara-

tively small area, minor damage from blast and flying fragments can be experienced over quite a wide radius. Apart from a direct hit, the chief danger is from flying fragments which have high enough velocity to pass through steam pipes, machine casings, switch tanks, etc. Turbo-alternators can be encased in reinforced concrete shells, as shown in Fig. 548 to 550, whilst the turbine house, basements and auxiliary annexes can be divided by 14 in. bulkhead brick walls. It should be pointed out that direct hits by high explosive shells cannot be entirely guarded against unless underground stations are used. The widest possible separation of plant and buildings appears to be the only solution to this problem. Possibly the best way to avoid a direct hit is by "blacking out"

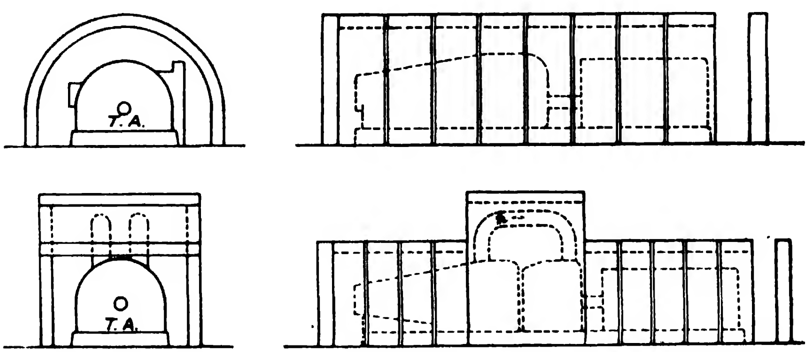

Fig. 548. Reinforced Concrete Covers for Turbo-Alternator Protection.

the station, and even this may prove futile if the surrounding locality is set ablaze by fires resulting from bombing of stores, etc. If this aspect be taken into consideration it would appear that a well-thought-out system of camouflage is essential. The use of portable power plants either in the form of boats, barges, railway and road vehicles have been suggested. The capacities of such plants must, however, be limited, although their availability for emergency services may prove very useful for starting-up purposes or special repair work. Considering the individual items of plant, a boiler wall may collapse, steam or feed pipes may fail, turbine control and governor gear may be damaged, transformer and circuit-breaker tanks and bus-bar chambers may be punctured. Outdoor transformers, switchgear and reactors should have roof screens to guard against falling splinters and small incendiary tube bombs. Wooden cooling towers are particularly susceptible to damage by

blast, but the concrete hyperbolic type is almost immune from such damage. Such eventualities amongst many others must be borne in mind and the provision of remote control centres to operate the affected plant should be considered. The inclusion of emergency sectionalising valves with remote control are useful. Underground and racked cables have been subject to damage and they take longer to repair than overhead lines, especially the higher voltage cables.

The protection which can be afforded to buildings depends primarily on their design and construction. Flat roofs can be

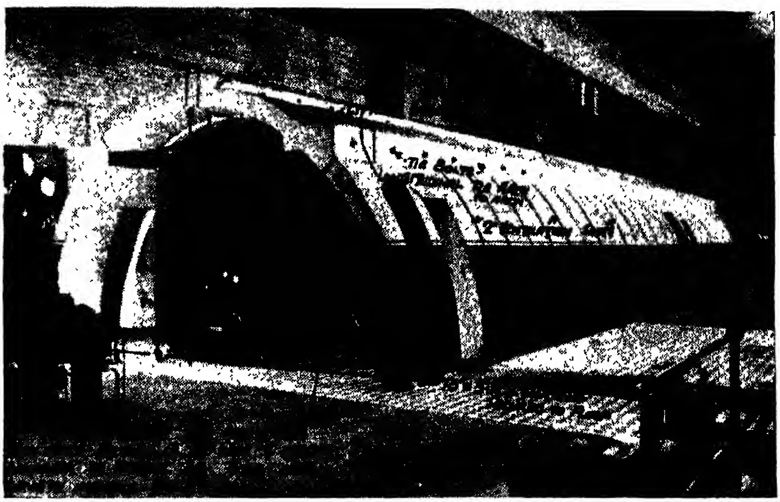

FIG. 549. Reinforced Concrete Blast and Splinter Protection for 20 MW Turbo-Alternator.

reasonably protected by piling up sandbags, but even then direct hits cannot be provided for. Roof and wall windows may be protected by bullet-proof shutters or the latter may be placed high in the walls and be long and narrow. Experience indicates that the damp-proof course is the weakest part of the structure in a brick building, and in some cases the walls have moved some 2 to 3 in. due to the blast. The use of blue bricks would overcome this defect. General experience has revealed that screen walls, bricking up of windows and strengthening of roofs, all designed to fortify the plant against damage by blast and splinters from bombs bursting outside the buildings, have proved very effective. The blast effect of a bomb exploding inside a turbine house at base-

ment level or below operating floor level is perhaps more local than was originally expected, but if exploding between roof and operating floor extensive damage to plant can result by blast and splinter. Damage to circulating water pipes can cause serious flood-

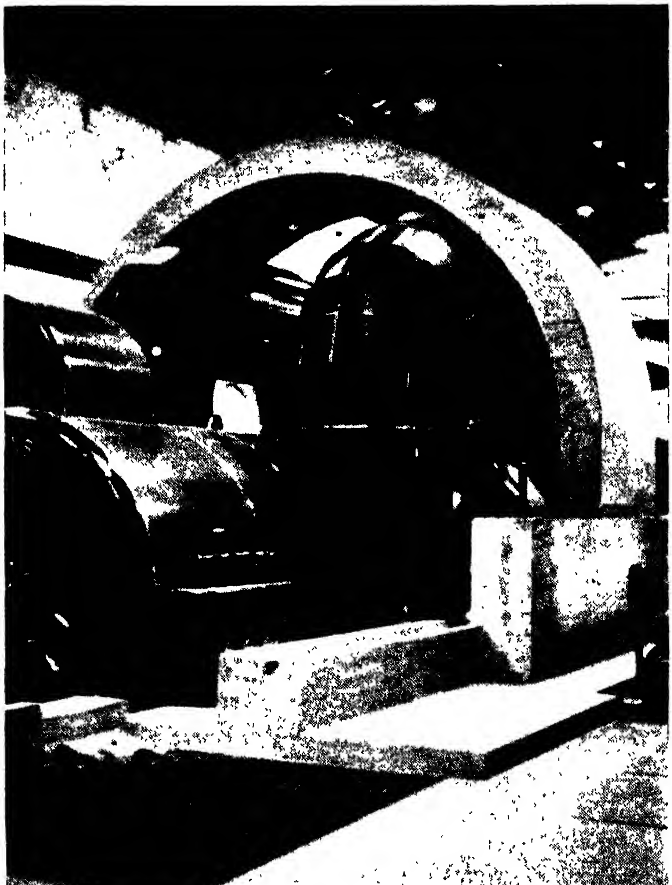

FIG. 550. Reinforced Concrete Blast and Splinter Protection for 30 MW Turbo-Alternator (part erection).

ing of the station basement and remote operation of valves has proved useful. The provision of adequate openings in all buildings and more especially in switch-houses for the " escape " of blast has proved successful. These openings should, where possible, be in the outside walls or in the roof, or both.

Apparently the effects of high explosives are not so detrimental as the effects of fire, and the simplest way of minimising fire damage is to limit the use of combustible materials. Buildings should be designed so that all loads are carried by a framework of steel; load-bearing walls are dangerous. Partitions should be framed in steel or reinforced concrete, independent of the main structure. The steel frame should be designed to resist collapse even if one main member be removed, and in this respect use may be made of supporting stanchions. External walls should be regarded as protective screens against weather and bomb fragments. Panels should not be built into the webs of stanchions but merely butt-jointed. A height of 6 to 7 ft. is apparently sufficient to give lateral protection, and remainder of the wall may be sheeting on steel framing designed so that blast will not be transmitted to the main framing. Roof glazing should be eliminated, and any explosion vents should be of suitable brittle material arranged to blow off harmlessly.

The necessity for maintaining black-out conditions needs no elaboration, but the difficulties are multiplied unless special consideration is given to the systems of lighting to be provided for. Lamp manufacturers have devoted considerable thought to this problem and some very satisfactory results have been obtained. The supplies to these systems should above all be reliable and no doubt the normal emergency D.C. supply has much in its favour. The A.C. lighting supply should preferably be taken from separate lighting transformers to avoid confusion with station auxiliary supplies. By having separate control of the lighting system the number of points for opening in the event of an emergency are reduced. Special communication circuits should be permanently installed for use throughout the station and also to the local A.R.P. and fire brigades. Attacks by enemy aircraft usually take the form of high explosive, incendiary and gas bombs, as low flying is dangerous and machine-gun fire is therefore not likely to be encountered. Regarding incendiary bombs, these have to be extinguished by stirrup pumps with variable jets and sand. Sand buckets and containers together with long-handle shovels should be placed at convenient positions to deal with such bombs.

Gas drill has been undertaken by numerous authorities and members of power station staffs have been included in training and practice courses. A number of the staff should be trained as dressers to the operators and also given a thorough knowledge of the work relating to decontamination. If decontamination is carried out on

the station site a building equipped with dressing and undressing compartments, baths, showers, bins for contaminated clothing and a first-aid room for treatment of gas casualties will be necessary. All entrances should be fitted with air locks. It is usual to have another building adjoining the decontamination centre in which are housed the boiling coppers for treating all contaminated equipment and anti-gas clothing and an extraction fan is installed to take away any gas fumes. A central first-aid post is also desirable so that the wounded may be treated immediately. It should also be kept in mind that following an air raid in which direct or nearby hits are registered prompt attention must be given to the buildings and plant. Maintenance and demolition squads should be trained for such work. The use of atom bombs and controlled missiles may also have to be considered in future civil defence schemes although, like the use of gas, may not be brought into effect in the event of another conflict.

War Hazards. Of the five main war hazards, sabotage, bombs, fire, barrage balloon trailing cables and aeroplanes crashing into overhead lines, the last two have caused the most trouble, more so than bombs. The breaking loose of balloons has caused many faults due to trailing cables, but the introduction of a ripping device causes them to deflate when they break loose and so fall quickly to earth.

CHAPTER XXIV

HYDRO-ELECTRIC PLANTS

THE increasing demand for electric power for industrial, commercial, agricultural and domestic purposes, together with the high cost of coal, has focussed considerable attention upon the need for comprehensive water power development. With the continued rise in coal prices and depleted reserves, coupled with an ever-increasing demand for electricity and a shifting load centre, large-scale hydro-electrical development will in all probability become an economic proposition. The Water-Power Resources Committee in their report of 1921 aptly stated that "The choice lies between developing a permanent source of power the value of which cannot but increase as time goes on, and using up in a comparatively inefficient way our irreplaceable stores of coal."

Interconnection of power transmission systems is well established, but it is questionable whether full use has been made in this respect of the advantages accruing from combined hydro and steam electric power production.

It is evident that almost all water-power commercially available should be utilised, and the development of such projects will no doubt be expedited and progress will continue for some time. The fact that water has been allowed to "run to waste" has frequently been held to be evidence that its utilisation would result in the production of cheap electric power, but it will be appreciated that economic factors must be considered for each project.

In 1909 Sir Winston Churchill wrote of the Owen Falls in his book "My African Journey": "So much power running to waste, such a coign of vantage unoccupied, such a lever to control the natural forces of Africa ungripped, cannot but vex and stimulate imagination, and what fun to make the immemorial Nile begin its journey by diving through a turbine." The Owen Falls hydro-electric scheme was put into commission during April, 1954.

A water-power site is usually developed for one of two purposes:—

(1) To supply electric power to a specially established industry or community, with annual load factors varying from 80 to 100 per cent. for industry, and 20 to 40 per cent. for a community.

(2) To provide additional power to an existing or proposed interconnected electrical system.

The interconnection of a hydro-electric station with a large system facilitates planning, and within certain limits enables the generating plant to be chosen almost regardless of the load to be served. This flexibility assists the economic development of the electrical system, and permits the exploitation of water-power sites which would otherwise prove uneconomical.

Use can also be made of an existing interconnected system to transmit power from the hydro-electric station to the load centres, and the extra capital expenditure for transmission would be reduced.

The major difficulty in utilising water-power in the past was that the distance between the best site for erecting the plant and the load centre was usually so great that bulk transmission was either impracticable or uneconomic. Water-power sites must be considered on their merits, for each site will possess certain special features seldom found in others, *e.g.*, facilities for development economically in easy stages; a central accessible situation in a healthy climate within reasonable distance of all possible load centres; a large catchment area with a heavy and well-distributed rainfall; extensive storage areas where reservoirs can be constructed at a small cost, and a very high head.

In some countries waterfalls have very high heads, and in consequence the power plant required is relatively cheap; also, owing to the large number of small lakes, there are good natural conditions for building the necessary basins for storing water. Reservoirs can be constructed in mountain areas where it is fairly cheap to acquire rights of development and pay compensation for damage; and solid rock is usually found at places where the dams and power plants are constructed.

Many countries are favoured with great natural resources in the form of water-power, and the developments in long distance transmission and interconnection, together with the advances made in the design and construction of hydro-electric generating plant, have made possible a wider utilisation of these resources. The available water should be utilised to the maximum advantage under the best commercial conditions.

The greater portion of the water-power resources of Britain are contained within the Highland Area of Scotland. Estimates of available water-power often vary considerably, as will be observed from the following :—

	Output Million kWh. per Annum
1921, Water Power Resources Committee . .	1,880
1938, Highlands and Islands Economic Committee	1,972
1942, Cooper Committee (Secretary of State) (undeveloped resources) . . .	4,000
1944, Hydro-Board Development Scheme (potential power resources) . . .	6,274

It has been stated that a careful examination and tabulation may show that the total potential power resources are very much larger than this. The approximate resources of output in MW are given in Table 93.

TABLE 93. *Water-Power Resources*

	Area Square Miles.	Estimated Continuous Output. MW.	Percentage of Total.
England . .	50,050	30	11
Wales . . .	7,380	40	15
Scotland . .	27,410	200	74
Total .	84,840	270	100

Generally speaking, the commercial utilisation of any water-power site is governed by the following factors :—

(*a*) Capital costs necessitated by the construction of the plant, civil engineering works, and purchase of water rights.

(*b*) Capital cost of transmission lines and the annual losses of power associated with transformation and transmission.

(*c*) Costs of production, as compared with steam, gas, oil, possibly at some more convenient site near the load centre.

Water-power schemes are varied and range from a 3-ft. fall on a river or canal, up to that of a 5,000-ft. fall in a range of mountains, and from utilising the whole flow from the catchment area of a great river down to that from a few square miles of country with heavy seasonal monsoon rainfall.

The power may be obtained from the natural flow of a river or canal alone ; or from the same supplemented by storage ; or from stored water alone.

In hydro-electric power practice, the actual fall may be either a natural water fall, or an artificial fall created by a dam or weir,

or a fall developed by carrying the water along a canal until a sufficient drop has been established above the original or more rapidly falling source. Existing weirs in tidal portions of rivers can also be utilised providing care is taken to allow for the effect of the tides on the operation of the turbines.

Hydro-electric power plants have certain operational advantages which, in addition to economic considerations, commend their application to large interconnected electrical systems. Some of the advantages are :—

(1) Almost instant availability for service. Can be run up and synchronised in a few minutes, and load can be increased or decreased rapidly.

(2) Very high reliability. Plant is simple and robust, and maintenance costs are low.

(3) Able to respond to rapidly-changing load without difficulty.

(4) No stand-by losses.

(5) Efficiency of plant does not change with age, except for certain replacements and providing good maintenance is ensured.

(6) Fewer highly skilled engineers required, and also fewer operatives.

(7) Cost of production varies little with passage of time.

(8) No fuel charges. No fuel is required, and there are therefore no transport charges in connection with handling, storage, or with disposal of refuse.

Fig. 551 shows a simplified flow sheet.

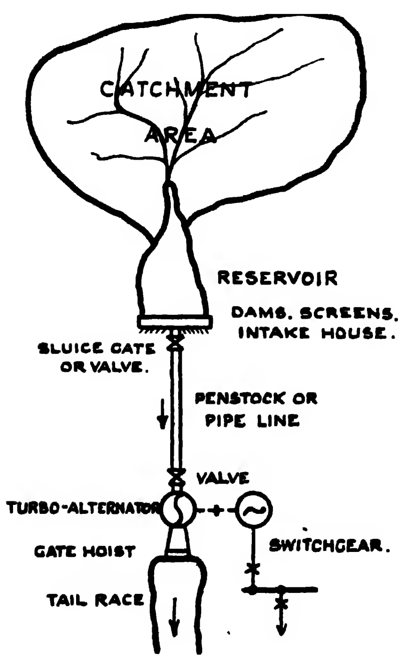

FIG. 551. Flow Sheet.

Continued improvement in steam-plant makes it more difficult to justify the use of water-power for base-load purposes, but increase in coal cost or a reduction in the rate of interest on capital expenditure, has the reverse effect.

In spite of the importance of water-power, many of the potential sites must of necessity

prove uneconomical, either on account of their distance from the load centres, lack of transport, or from the fact that storage would prove too costly. The extent to which a scheme is capable of economic development can only be determined after a careful review of the catchment area and site of the proposed works, and a prolonged investigation of the run-off or rainfall records.

Hydro-electric stations are usually located in wild, mountainous districts, remote from shopping and recreational centres. The lack of social services normally provided in more populous areas, more especially in respect of health, education and recreation, will deprive families of such facilities.

These power stations are, of necessity, situated in non-populous areas, but taking everything into consideration it is usually contended that the disadvantages are compensated by the advantages of healthier surroundings and living conditions, cheaper rents, and the general amenities which are to be found only in the countryside. Further, the advent of motoring and the better public travelling facilities in rural areas, together with the widespread use of radio, and television, have all improved the lot of the remote country dweller.

In practice it is found that some men prefer the quieter life that the country offers, and the service of these men extends for lengthy periods. The absence of distraction may also afford opportunity to certain men to further professional study and technical advancement. A great deal of research work can be undertaken in connection with problems arising from the constructional and operational work, such as geological surveys, rainfall, river flows, the design of dams and fish passes, and water investigations, etc.

It is quite usual to receive objections from interested bodies to the building of hydro-electric plants, and these often lead to considerable delay. Many object, on principle, to the exploitation of the water resources of mountainous regions without regard to the amenities, the local inhabitants, the value of mountaineering as a sport and from the National point of view. The objectors contend that power houses, leats, dams, pipelines, pylons, concrete access roads, and spoil from the tunnels, etc., cannot improve the scenery.

Long periods of dry weather can endanger supplies, and the problem of providing standby generating plant may have to be considered. In Switzerland, where hydro-electric power predominates, serious restrictions on electricity supply are sometimes inevitable. Only once, during the winter of 1857–58, was the level

of the Rhine lower than in 1949. That, and the heavy drain on the artificial lakes—some of which were half empty—justified new restrictions on electricity consumption which were enforced. Space and water heating, shop-window lighting and floodlighting were almost completely banned. Street lighting and lighting in the homes were reduced by one-third, and industry had to halve the previous year's already curtailed consumption. Train services were also affected.

FUNDAMENTALS

The basic elements of potential water-power are :—

(1) River or stream flow.

(2) The available head or fall through which the flow may be utilised in the production of power.

Water in motion possesses energy by virtue of its velocity, its pressure and its height. It has kinetic energy, pressure energy and potential energy.

$$\text{Kinetic energy} = \frac{V^2}{2g} \text{ ft. lb. per lb. of water.}$$

$$\text{Pressure energy} = \frac{p}{w} \text{ ft. lb.}$$

$$\text{Potential energy} = H \text{ ft. lb. per lb. of water.}$$

V = velocity in ft. per sec.; p = pressure in lb. per sq. ft.; w = density or weight per cub. ft.; H = its height in ft. above some datum level.

1 cub. ft. water	= 6·235 imperial gallons.
	= 62·35 lb.
1 acre-ft.	= 43,560 cub. ft.
1 sq. mile ft.	= 27·88 million cub. ft.
1 water H.P.	= 550 ft. lb. per sec.
	= 8·83 cub. secs. ft.
Theoretical water H.P.	$= \dfrac{\text{cub. ft. per sec.} \times \text{head ft.}}{8{\cdot}83}$

The theoretical water horse-power available from a supply of Q cub. ft. per sec. (cusec.) under a net head of h ft. is equal to

$$\frac{62{\cdot}4 \,.\, Q \,.\, h}{550}$$

With a turbine efficiency of n, the B.H.P. at the turbine shaft is $\dfrac{62{\cdot}4 \,.\, Q \,.\, h \,.\, n}{550}$ or kW. $= \dfrac{62{\cdot}4 \,.\, 746 \,.\, Q \,.\, h \,.\, n}{550 \,.\, 1{,}000}$.

If the efficiency of the electric generator is n^1, then the E.H.P. at the switchboard is $\frac{62{\cdot}4 \,.\, Q \,.\, h \,.\, n \,.\, n^1}{550}$ or kW. =

$$\frac{62{\cdot}4 \,.\, 746 \,.\, Q \,.\, h \,.\, n \,.\, n^1}{550 \,.\, 1{,}000}.$$

The gross or total head H is the vertical difference in level

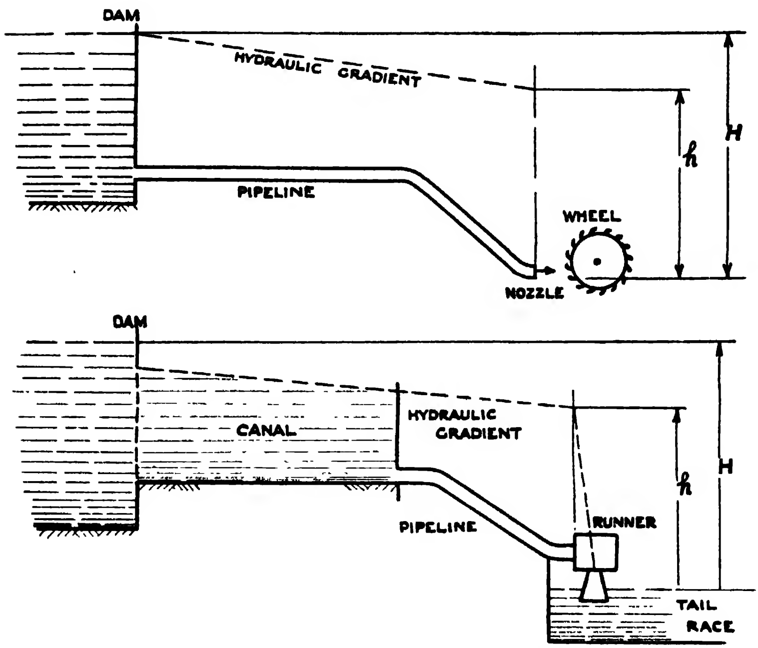

FIG. 552. Available and Effective Heads.

between the level of the water where it is tapped at source and that of the tail race where it is finally discharged (Fig. 552).

There are a number of deductions to be made before the net or working head available for operating the turbine is obtained. These include the frictional losses in the pipe lines, casing, draught tube, etc. If an open channel or canal is used above the forebay, the slope will have to be allowed for, also the losses at the screens and weirs in it.

To avoid flooding, the plant may be located above the normal level of the tail water, and with impulse turbines this head is lost.

In practice, the total head can rarely be utilised at all times under all operating conditions.

A catchment area is the whole area draining into a river or stream at any particular point in its course. In planning the extent of land to be regarded as catchment area, the calculations from rainfall statistics are apt to be unreliable. This is due largely to the varying amounts of water held by the surface of the land over which the rain falls. If the entire rainfall within a catchment reached this point in a river, then

1 in. of rain = 100 tons or 3,600 cu. ft. per acre.
= 64,000 tons or 2·33 million cu. ft. per sq. mile.

In calculations regarding power output it is useful to remember that 1 cusec. = 1·13 sq. mile ft. per annum, *i.e.*, 1 ft. of water over an area of 1 sq. mile gives a flow of 1 cusec. for one year.

Energy available under the most favourable conditions is :—

(1) From flow

$$\text{kWh.} = \frac{\text{cusecs.} \times \text{head ft.}}{15} \text{ approx.}$$

(2) From storage

$$\text{kWh.} = \frac{\text{thousands cu. ft. stored} \times \text{head ft.}}{56} \text{ approx.}$$

$$\text{or kWh.} = \text{millions cu. ft. stored} \times \text{head ft.} \times 17 \text{ approx.}$$

The following example indicates the method of estimating the power available under given conditions :—

A hydro-electric power plant has a catchment area of 30 sq. miles and the run-off is 70 per cent. The average rainfall is 50 in. and the head is 1,350 ft. Find the power available if the overall efficiency of the plant is 80 per cent.

$$\text{cusecs. available} = \frac{\text{catchment area sq. miles} \times \text{annual rainfall, ft.} \times \text{run-off}}{1{\cdot}13}$$

$$= \frac{30\,.\,50\,.\,0{\cdot}7}{1{\cdot}13\,.\,12} = 77{\cdot}5.$$

$$\text{Power available} = \frac{62{\cdot}4\,.\,746\,.\,Q\,.\,h\,.\,n\,.\,n^1}{550\,.\,1{,}000}$$

$$(e = n\,.\,n^1 = 80 \text{ per cent.}) = 0{\cdot}0845\,.\,Q\,.\,h\,.\,e$$

$$= \frac{0{\cdot}0845\,.\,77{\cdot}5\,.\,1{,}350\,.\,0{\cdot}8}{1{,}000}$$

$$= 7{\cdot}1 \text{ MW.}$$

This assumes that the whole of the water is stored and used for power production.

The extent to which storage is necessary is governed largely by the nature of the prospective load and also by the effective head available. In general, there are three classes of supply :—

(1) Continuous Supply.

(2) Restricted Supply.

(3) Emergency Restricted Supply—Drought and Winter Conditions.

For a given maximum load (1) requires the largest storage provision.

The load factor of a station is defined as the percentage of the average load over a given period (week, month or year) to the maximum load over a predetermined time, usually one-half hour.

$$\text{Annual load factor} = \frac{\text{units generated per annum.}}{8{,}760 \times \text{maximum demand}}$$

It will be appreciated that the value of the load factor will never be greater than 100 per cent.

The diversity factor at the station switchboard is defined as a percentage of the arithmetical sum of the maximum demands on the outgoing feeders over a given period of time to the total maximum demand sent out at that time. Its value is never less than 100 per cent. (unity).

The utilisation factor is the ratio of the water used for power production to that available in the river. With a constant head, utilisation would also be the ratio of power used to that available, but generally there will be but little difference in the factor whether expressed as a ratio of water or power.

The capacity factor or plant-use factor is the ratio of the average output of the plant to the plant capacity. It will be identical with load factor when the maximum load equals the plant capacity.

The essential features of a water-power project are :—

(*a*) The Dam or Weir—to create a head and provide a large area or pond of water.

(*b*) The Inlet Waterway—canal, pipeline or a combination thereof.

(*c*) The Power House and Plant—turbines, alternators, buildings and auxiliary plant.

(*d*) The Tail-race or Outlet Waterway—from the power house to the river.

It would appear that in the planning of any scheme, two methods of approach are possible, each playing its part in the economic aspect :—

(1) To construct and operate as a base-load plant.
(2) To construct and operate as a peak-load plant.

The effect is illustrated by taking two typical examples :—

(1) Assumptions : The water-shed provides sufficient water for an output of 200 million kilowatt hours per annum ; the plant operates at 100 per cent. load-factor.

$$\text{The generating plant required} = \frac{200 \,.\, 10^6}{8{,}760 \,.\, 1{,}000}$$
$$= 23 \text{ MW approx.}$$

(2) Assumptions : The water-shed to be used for peak purposes ; the station operates at 20 per cent. load-factor.

To generate 200 million units the plant-capacity will have to be :—

$$\frac{23{,}000 \,.\, 100}{20 \,.\, 1{,}000} = 115 \text{ MW.}$$

Such reasoning mainly affects the generating plant installed, as the major constructional works are almost identical in both cases. The point to be remembered is that a peak-load station permits the use of any unforeseen increase in water flow, thereby supplying extra units at almost no additional cost. The effects of providing for peak-load as compared with base-load on the principal items making up the cost of a scheme are as follows :—

(1) Preparation and promotion of scheme .	Same cost.
(2) Aqueducts collecting and conveying water to reservoir, and works other than for (4)	Same cost.
(3) Land and compensations other than (4)	Same cost.
(4) Reservoirs and flooded land, and road diversions around reservoirs . .	Saving.
(5) Pressure tunnel	Increase, but not in proportion to capacity.
(6) Pressure pipes	Increase with increase of capacity.
(7) Power station and plant . . .	Increase with increase of capacity.

The basis for fixing the plant capacity is a flow-duration curve at the particular site under consideration.

The capacity is theoretically a problem of economics, or, in other words, that plant capacity which shows the greatest net return in value of electrical power sent out.

The design depends on the type of load to be supplied, and when the load-factor is high the turbine capacity for a given annual output is considerably smaller than when the load-factor is low and the capital costs are correspondingly lower.

Unnecessary increase in capacity adds to the cost of plant, and, in many cases, the cost of the foundations.

The load-factor and the purposes for which the power produced is to be used, together with the revenue realisable, all have to be carefully considered. The problem of stand-by plant must also be kept in mind.

When the total plant capacity has been decided upon or tentatively assumed, it is then necessary to fix the sizes of the individual machines. For a given capacity of plant installed, the cost of the power plant and its associated foundations is directly proportional to the number of machines. The cost of plant—turbo-alternators, switchgear and auxiliaries—increases with the number of machines, but not quite in direct proportion to this. From an operating point of view, it is usually desirable to have as few machines as practicable consistent with safe and economical operation.

Catchment. The amount of power capable of development in any individual catchment area is dependent on the amount of storage available in relation to the yearly distribution of the run-off. In this respect, some catchment areas are very favourable as the facilities for storage are good on account of the natural configurations of the area. The development of two or more water-sheds as a unit is quite practicable and frequently proves more favourable. In arriving at the most suitable method of co-ordinating the respective water-sheds and determining the economic limit of maximum power to be developed in any of the stations, all the factors of maximum and minimum water flow and its variation throughout the year, in combination with maximum peak loads, load-factor and diversity-factor, must be considered.

In some countries it is the practice during each spring to survey the catchment areas of certain power schemes so that an estimate can be made of the total snowfall which must melt and run off. It is then possible to calculate fairly closely how great the total output of power for the year is likely to be, and thus to inform the larger consumers which draw their supplies therefrom, at what rate it can be used.

Figs. 553 and 554 show two catchment areas, and Tables 94 and 95 give hydraulic and technical details relating to a number of schemes.

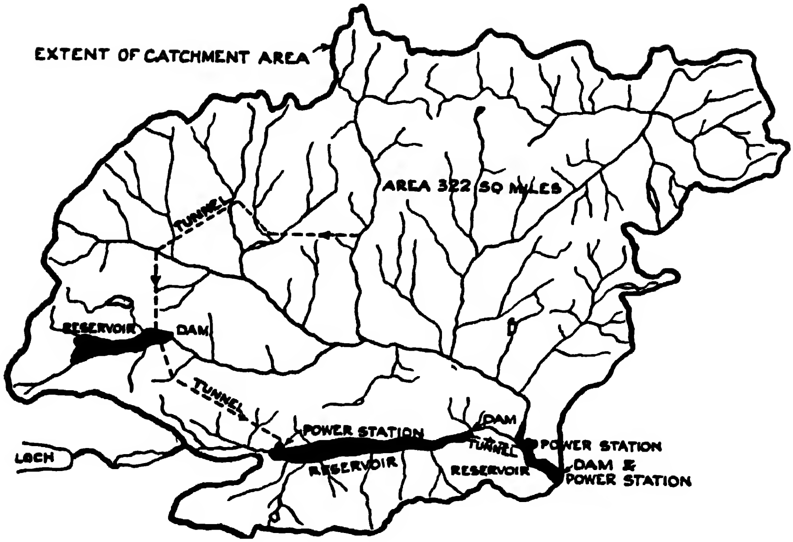

Fig. 553. Catchment Area.

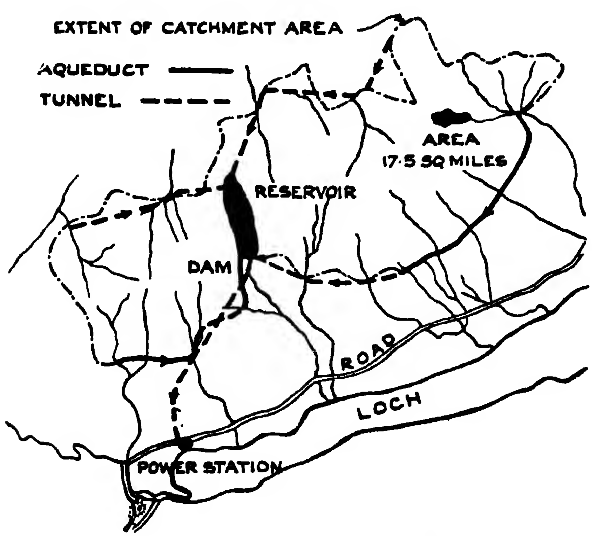

Fig. 554. Catchment Area.

TABLE 94. *Station Hydraulic and Technical Details*

Scheme	Dam	Catchment Area Square Miles	Annual Rainfall Inches	Gross Head Feet	Plant	Annual Output Million kWh.	Storage Per cent.
A	Buttress type 1,160 ft. × 165 ft. high	32	115–120	910	4—32·5 MW Vertical Francis; 1—450 kW. Pelton Wheel House Set.	130	15·5
B	250 ft. × 56 ft. high	7·3	68	490	2—500 kW. Pelton Wheel, 4 MW possible development.	4	
C	1,250 ft. × 130 ft. high	17 5	87	1,362	1—30 MW Horizontal Pelton Wheel.	71	17
D	1,500 ft. × 20 ft. high	56	79	557	2—12 MW Vertical Francis.	83	83
E	1,000 ft. × 90 ft. high	15	80	400	2—3 MW Horizontal Francis.	13·5	14·3
F	1,310 ft. × 127 ft. high	86	55	610	3—25 MW Vertical Francis.	103	15·5
G	386 ft × 65 ft. high	515	60	173	3—19 MW Vertical Francis.	143	27·5
H	475 ft. × 54 ft. high	54	55	50	2—7 5 MW Kaplan	54	22

TABLE 95. *Station Hydraulic and Technical Details*

	Schemes				
	A	B	C	D	E
Catchment area . sq. miles	150	170	190	50	400
Average annual rainfall . in.	60	60	60	60	60
Average run-off . . in.	50	50	50	50	44
Highest water level in reservoir . . . ft. O.D.	510	340	245	580	120
Lowest water level in reservoir . . . ft. O.D.	500	335	240	540	110
Gross fall . . . ft.	170	70	70	410	110
Average net fall . . ft	150	65	65	365	100
Plant capacity . . MW	2–10	2 6	2 6	2 12 2 -500 kW. HS.	3–11 1–250 kW. HS.
Maximum flow for power cusecs.	1,900	2,400	2,400	800	5,000
Annual output millions, kWh.	35	20	20	400	70

SITE SELECTION

One of the ideal features which makes the planning of hydro-electric development comparatively economical is a good system of natural storage lakes, at high altitudes, with substantial catchment areas. Geological, geographical and meteorological conditions all require investigation. Aerial photography is used in conjunction with ground surveys to produce general maps of the terrain required for investigation of alternative developments. Detailed ground surveys are limited to areas of the proposed works. Geodetic surveys, triangulation and precision levelling are necessary to enable precise determination of the relative positions of all permanent survey points throughout the area and the calculation of the variation in gravitational force and in the earth's magnetic field to be carried out. This data is essential for the successful construction of long tunnels which may be required to be driven through a range of mountains.

The essential characteristics are large catchment areas, high average rainfall, steep gradients and favourable sites for impounding reservoirs. Mountain ranges of comparatively high altitudes with steep slopes amenable to a large run-off (impermeable strata) are suitable. Disintegrated granite at the surface of rock formations provides much ground storage, so that flood flows are reduced, and in dry weather the stream flows are often well maintained, but the same conditions generally entail deep cut-off-walls for the dams of the reservoirs. Certain water-sheds may be utilised for town's water supply, and the growing demands in this direction will necessitate reserving further catchment areas. Co-operation can prove beneficial to all interests concerned. In some cases every effort is made to develop the potentialities of a lake as a holiday resort, in addition to providing power, and a centre of beauty and pleasure.

Many factors have to be given very careful consideration, but the following are probably the most important :—

(1) Water Available

The estimates prepared of the average quantity of water available should, wherever possible, be based on actual measurements of river or stream flow. Survey methods vary with the nature of the river. On calm stretches, echo soundings are taken from boats. In turbulent rivers soundings are taken from helicopters. In the

rapids, a lead weight is lowered on the end of wire from the helicopter to the river bed, and transit observations made from the shore, on a windsock attached to the wire enable depths to be determined. Variations in water level are recorded on gauges. The results of such observations can be transferred to a scale model of the whole scheme. In many cases reliance may have to be placed on rainfall records taken at various locations on the catchment area, and due allowance will have to be made for losses caused by evaporation, percolation, etc., in estimating the average quantity of of water discharged. Such a method is liable to considerable error where severe winter conditions obtain, or where the gathering grounds are subject to very heavy snowfall. Wherever possible the estimates should be based on recorded observations taken over a number of years so as to determine within reasonable limits the maximum and minimum variations from the average discharge. Excessive figures will only lead to higher capital charges due to the provision of larger civil engineering works and plant normally required to meet the load demands. Where plants are situated on or near the equator, the storage reservoirs or natural lakes have a very high evaporation loss. In some years the total evaporation actually exceeds the run-off, and the average loss may approach 93 per cent. of the rainfall, leaving only 7 per cent. of the rainfall for run-off to the river. This high rate of evaporation is partially attributable to extensive papyrus and other vegetation.

The essentials of stream-flow data are :—

(*a*) Daily, weekly or monthly flow over a period of years as a basis for plant capacity and estimated output, both of which are a function of the average flow in addition to its distribution during the year as indicated by flow-duration curves. If storage is envisaged, the records should preferably include one or more dry periods of years.

(*b*) Minimum or low-water flow as a basis for the provision of primary or dependable power. Such conditions may also fix the capacity of stand-by plant required, *e.g.*, steam, oil or gas turbine plant.

(*c*) Maximum or flood-flow conditions to provide a safe power plant installation with adequate spillway or gate relief, and also avoid damage by flowage to up-stream property.

(2) Water Storage

The wide variations of rainfall which obtain usually make it necessary to provide storage to afford a uniform power output.

A storage basin or reservoir is used for equalising the flow of water so that any excess at certain periods can be made available for maintaining output during times of very low-flow. Storage arrangements require a careful study of the topography and geology of the catchment area so that natural foundations can be used to best advantage. Such factors materially affect the selection of a site for a dam or the location of a pressure tunnel.

Maximum storage should be provided consistent with economical expenditure. There are two extremes in operating storage :—

(*a*) Where it is intended to almost empty the reservoir at the end of each " water year," *i.e.*, not carry over any water for the next season (yearly-use method).

(*b*) Where it is intended not to draw on the reservoir in excess of the safe yield which will have been estimated from a study of previous dry periods. (Safe yield or most dependable-flow method.)

Storage operation, more especially where other plants at some distance apart are also served, may be rather complex, for it is well-nigh impossible to forecast rainfall conditions and water supply for a given season. Therefore storage operation has to be based almost entirely upon a study of past performance. The reservoir may be located at or near the power plant, or, alternatively, some distance beyond it. In the latter position, there is an intervening uncontrolled area which may have to be accounted for in estimating the flow available at the plant. The holding and releasing of water at the reservoir may be used to equalise the daily or weekly fluctuations in stream flow, or permit regular hourly use of the water by the turbines to suit the fluctuations in local demand.

One catchment area in Switzerland is at 6,000 ft. above sea-level and freezes up in the winter so that almost the whole of the run-off takes place in the summer from the summer rains and the melting snow and ice. The station is a winter-load one, used to make up power and water to meet the winter deficiency at other stations. In order to serve its primary function, the reservoir has a capacity equal to one year's supply of water so that the whole of the run-off may be transferred to winter use.

(3) Head of Water

The topography of the water-shed, together with the water flow at all times, and the effect of building up of water in the tail-race as a result of turbine discharge or by floods, should be allowed for.

Low falls on unregulated streams are subject to wide variations which affect the net head, and may, in fact, reduce it to an abnormally low value should the tail-race be drowned.

For a given power output, every increase in effective head reduces the quantity of water to be stored, passed through tunnels, screens, pipe lines, and turbines, and therefore the capital cost of the scheme. In order to secure the highest possible effective head it is essential to bear in mind all possible factors which may affect it.

(4) Distance from Load Centre

When the power produced is to be utilised some considerable distance from the site chosen, then the question of the economic limit of transmission in respect of both distance and routes will have to be considered. The routes will have an important bearing on the cost of erection of the transmission lines, and their subsequent maintenance.

(5) Access to Site

Good access is always a desirable factor, but it is very important if the power is to be utilised at or near the site of the power plant, and due regard must be paid to the facilities for transport.

The final investigations to be made in any project under review should include the following :—

(*a*) The selection of the most suitable site should there be more than one under consideration.

(*b*) Obtaining full information to enable the plans, specifications, and cost estimates to be prepared.

It is possible that there are certain parts of a country in which there are a number of isolated communities which, although very small, are nevertheless of sufficient importance to justify early efforts to afford a supply of electricity. Maybe a supply could not be given for many years by transmission line from the main system, but it is often possible to make available a supply by developing the smaller local sources of power. These smaller schemes have also the future advantage, where they may be interconnected by long-distance transmission lines, of acting as supporting points for the maintenance of voltage and the continuance of supply in circumstances where the service may be interrupted for long periods due to failure of main transmission lines.

CLASSIFICATION OF PLANTS

There are broadly two divisions :—

(1) Schemes depending primarily on flow.
(2) Schemes depending primarily on storage.

Hydro-stations may also be classified as :—

(*a*) Manual (attended) plants ; and
(*b*) Automatic plants.

There are three types of plant with respect to head conditions, namely :—

(1) Low head ;
(2) Medium head ;
(3) High head ;

but there is no line of demarcation between a high and a medium head or between medium and low head.

The head conditions also affect the choice of type of turbine to be installed, affording a further means of classification :—

(*a*) Propeller turbine for low heads (1 to 150 ft.).
(*b*) Reaction turbine for medium heads (up to 1,000 ft.).
(*c*) Impulse turbine for high heads (above 1,000 ft.).

The turbines may be either of the horizontal or vertical types. Vertical machines require less space, and have other advantages mentioned later. Turbines of all three types are used on some schemes. In one comprehensive scheme, the types of turbines used are vertical and horizontal Francis, vertical Kaplan and horizontal Pelton wheels. The largest reaction turbine of the Francis type is 53,500 H.P., and drives an alternator of 40 MW capacity, and the smallest is 300 kW. with operating heads varying from 970 ft. down to 16 ft. The largest Kaplan turbine is of 18,500 H.P., coupled to an alternator of 13 MW capacity, and the largest Pelton wheel is 40,500 H.P. driving a 30 MW alternator.

Figs. 555 and 556 show layouts for low head plants.

Referring to Fig. 556, a dam is built to create a fall by raising the water level in a river above the dam ; any excess water flowing over the top of the dam, which forms a spillway. The other alternatives all give a larger spillway area because the whole of the crest of the dam serves to discharge water. Where a dam has to be built across a river flowing through a narrow gorge, the spillway should run the entire width of the dam to prevent flooding in the

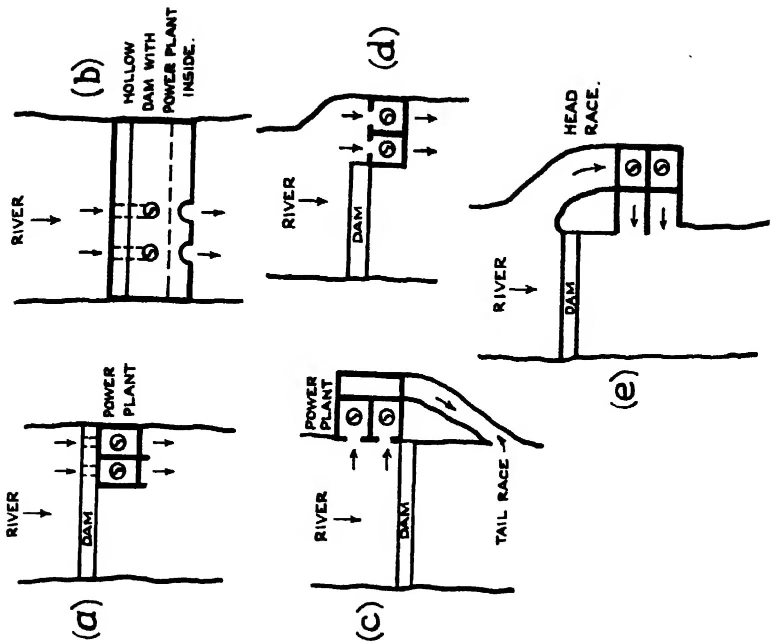

Fig. 556. Low Head Developments.

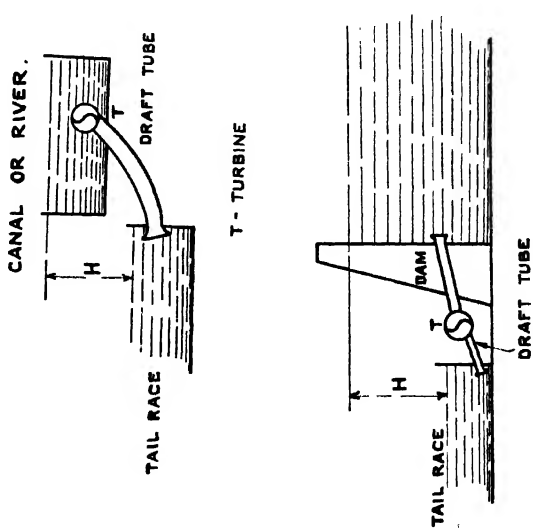

Fig. 555. Low Head Plants.

upper approaches. If the power station is constructed at the side of the river, the costs will be high on account of the considerable rock excavation. A hollow dam with the power plant accommodated inside overcomes this difficulty, and the entire length of the crest of the dam can be utilised to discharge flood waters.

In medium-head layouts, the water is usually tapped off to a

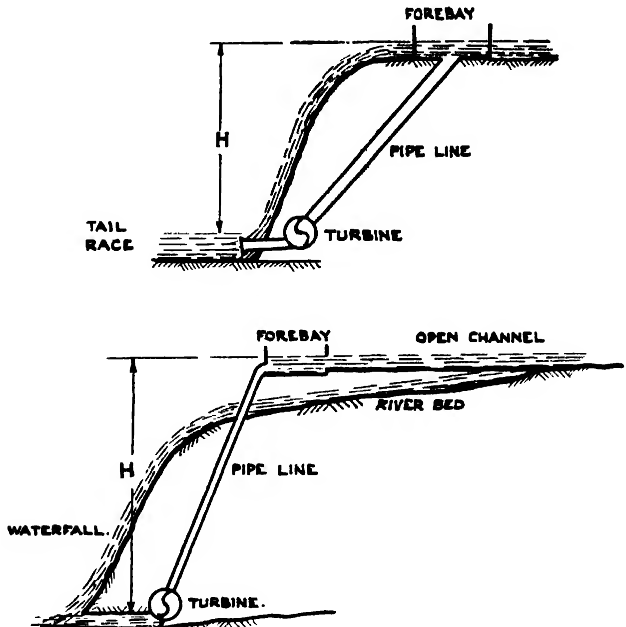

Fig. 557. Medium Head Plants.

forebay on one bank, and pressure pipes run to the turbines which discharge below the fall (Fig. 557).

With reaction and propeller type turbines a draught or suction tube is used, which is carried below the water level of the tail-race, so that the gross or total head is the difference between the forebay and tail-race levels. If an impulse type turbine is used on such a fall, the gross head is the difference between the levels of forebay and jets.

A spillway should be included to carry the entire discharge of the channel unless storage is provided, and so allow for sudden plant unloading or complete stoppage.

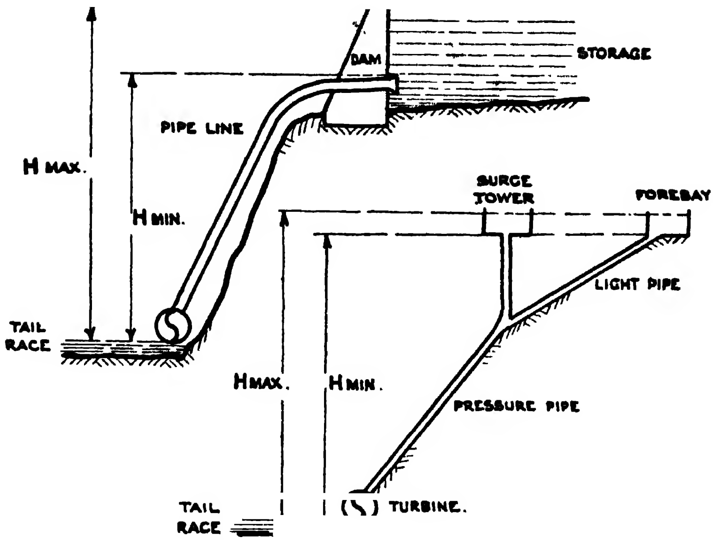

FIG. 558. High Head Plants.

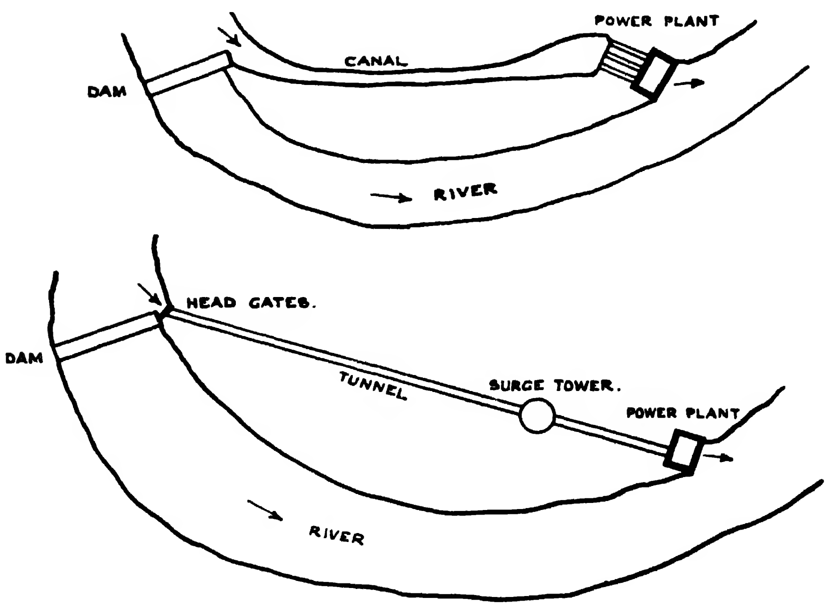

FIG. 559.

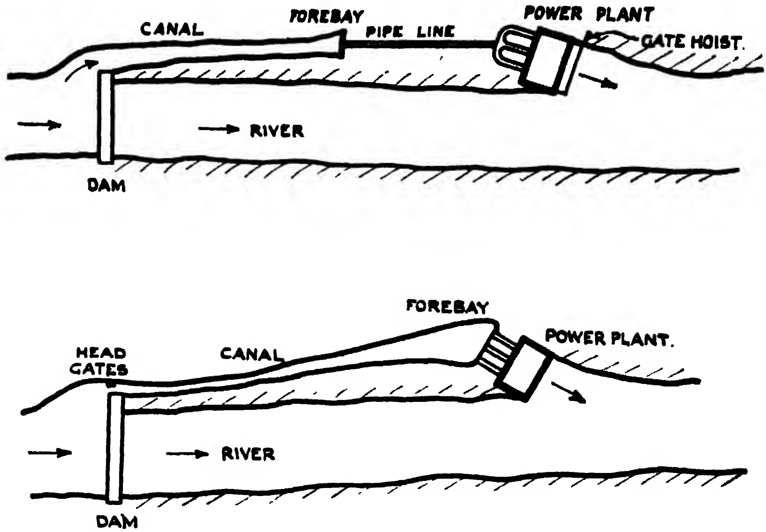

FIG. 560.

The amount of storage depends to some extent on the properties of the ground at the dam site, and also the extent of the permissible up-stream flood level with a full reservoir.

It sometimes happens that the physical characteristics of the surrounding area permit of a pipe line to be constructed for only a portion of the fall available, and in such cases it may be necessary to include a surge tower to act as a regulating forebay and shock

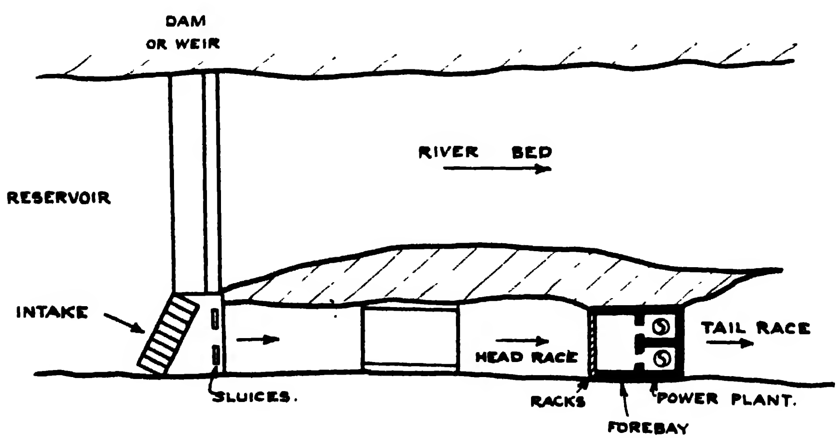

FIG. 561.

absorber. The pipe line from the tower to the forebay is, therefore, not subjected to the full head and need not be of great strength (Fig. 558).

Some time elapses before the flow becomes steady in a long pipe-line ; the water may run a mile or more, should the load-demand suddenly increase or decrease, and the surge tower is of such a capacity to deal with the interval.

Figs. 559 to 563 show other possible layouts to suit the site conditions obtaining, some of which can be applied to low, medium, or high-head plants.

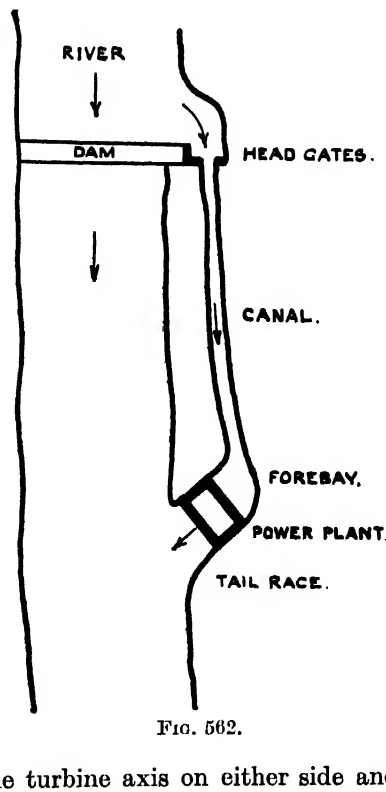

FIG. 562.

In Fig. 564 water from the storage reservoir, which may be a natural lake or a reservoir created by a dam, passes through a pressure tunnel to the pipe-line which supplies the power plant.

Some layouts permit the water to pass through the station building by way of apertures or canals arranged between the turbines and alternators. This may be necessary where the station extends the full width of a canal or river and it is deemed advisable to provide for the rapid discharge of the total or partial sudden drop in electrical load. This arrangement obviates the widening of a canal for a discharge weir, and reduces the capital costs. The discharge ducts through the building are arranged symmetrically about the turbine axis on either side and join above the draft tube ; in times of flood they have the effect of increasing the suction in the tubes. These ducts are provided with two sluices on the up-stream side the opening of which allows of the discharge of ice formations and also enables the levels and flow to be regulated for shipping and the supply to stations further down the river.

Some schemes are developed in stages having two or more

stations with a principal reservoir at high level at the top of the system, and subsidiary or balancing reservoirs between the stages to which further water from lower catchments is collected. Pumps are sometimes installed in the upper-stage power station for the

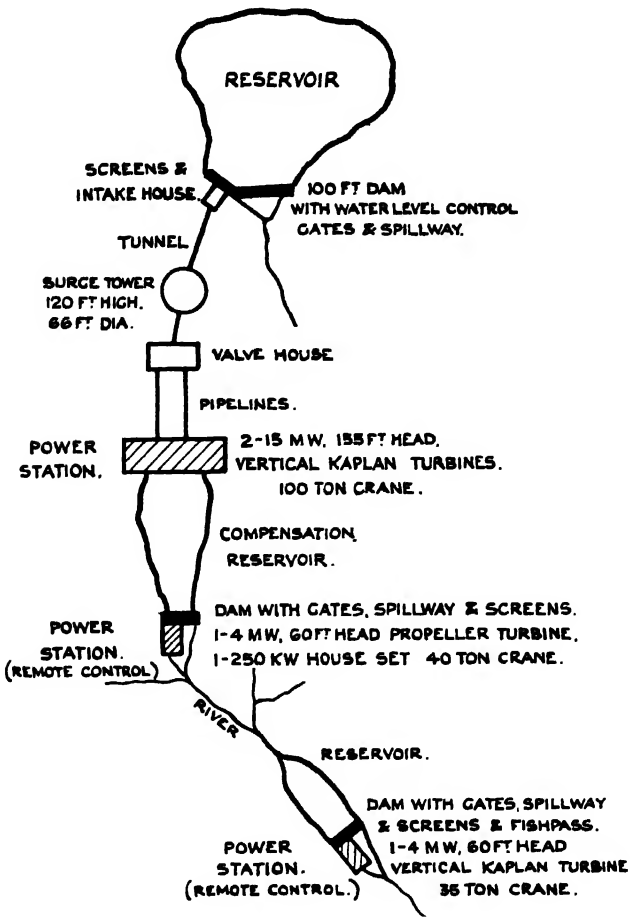

FIG. 563. Low and Medium Head Scheme.

purpose of pumping some of the water from the balancing reservoir, at times of surplus inflow, back to storage in the top reservoir during off-peak periods. It is probable that when there is surplus water to be pumped at one station, there will be surplus power available at other stations to provide power for pumping.

Automatic Plants. The simplicity and reliability of hydro-electric plant has made it particularly suitable for automatic control.

Small isolated catchment areas which would otherwise prove uneconomical if developed for manual operation, can usually be justified by the application of remote automatic control. With the proved reliability of automatic telephone equipment, it is possible to utilise this to operate the plant by supervisory control from some considerable distance without the need for a large number of pilot cables. A single pair of conductors used in conjunction with selective apparatus is capable of performing the necessary functions.

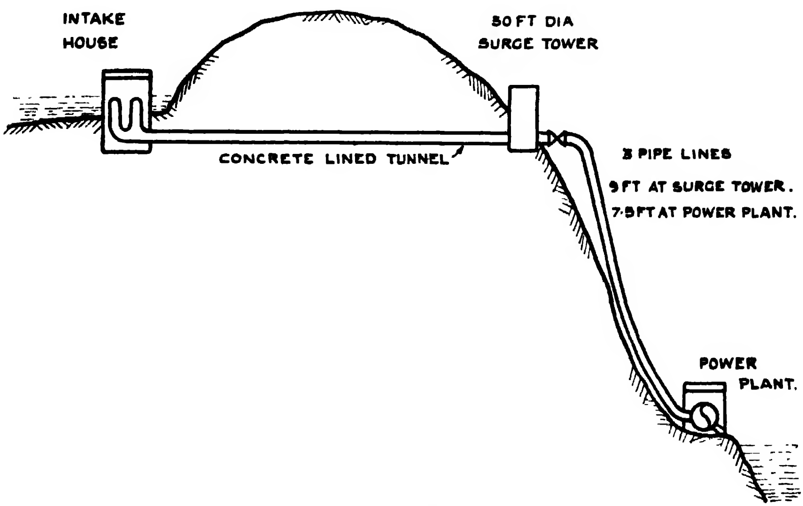

FIG. 564.

Automatic plants can be arranged to operate under :—

(1) Remote supervisory control from a main station or control centre, with automatic control of the turbines.

(2) On local control with automatic control of the turbines.

(3) Local control.

Periodical cleaning, inspection, and the usual routine maintenance on certain sections of the control equipment and generating plant are the only needs to be met by staff. Considerable savings are effected in salaries and wages, especially where there are a number of small automatic plants associated with a large scheme. Automatic control is eminently suitable for medium output stations which are only required to produce wattful power (kWh.), leaving

the frequency and power regulation to more conveniently situated plants.

Automatic control provides social as well as economic advantages and the additional cost of this equipment is largely compensated by other savings. Such equipment may determine the utilisation of power in very long valleys where a choice has to be made between concentration of the whole available water power in a single plant or spread over several smaller plants. The first has the advantage of lower initial and running costs, while the second enables construction to be carried out in stages so that the initial plants can be commissioned in much shorter periods and as desired.

PLANT LAYOUT

The nature of the development plays an important part in the choice of the plant arrangement. With low-head power plants the space is usually limited by the width of the dam on or within which it is built, and this, in turn, is primarily fixed by the space required by the turbines and alternators. In high-head schemes, the sites for the power plants can quite often be selected to give the desired layouts. The machines are usually placed in a row down the length of the main building or turbine house. Little or no difference is made if horizontal machines are placed parallel or at right angles to the longitudinal axis of the building. Sufficient space should be provided to facilitate the dismantling and subsequent re-erection of the machines, and where possible it is a decided advantage to preserve a repair bay at one end of the turbine house preferably near to the workshops.

In the design of any station, it is essential that safety of operation and reliability of supply should be kept uppermost in mind.

The possibility of complete or partial flooding due to failure of the hydraulic equipment or excessive rise of tail water level, may be responsible for introducing features which have an effect on station design.

The number and type of machines to be installed will depend principally on local conditions, but wherever feasible they should be as large as possible as the cost per kW. is reduced as the size of machine increases. Careful attention should be paid to the selection of stand-by machines, and these should be kept within reasonable limits.

For independent stations one stand-by machine will usually

suffice, but interconnection with other stations materially affects the choice of type and the number of machines to be installed. The layout will be affected by the type of plant to be installed, and the principal features to be reviewed in respect of reaction and impulse turbines are broadly summarised as follows :—

Reaction Machines. With vertical single-runner machines, the most convenient and economical layout is that with the machines in

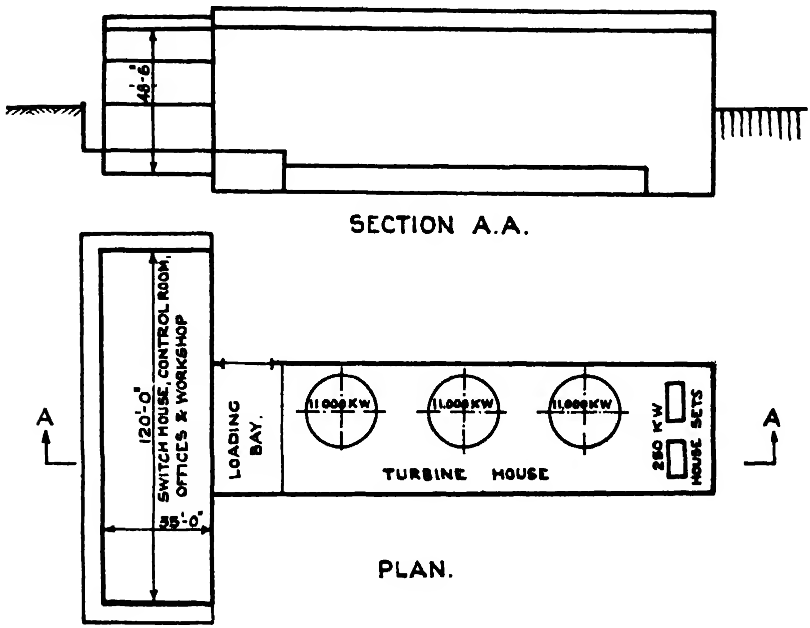

Fig. 565.

a line parallel to the length of the turbine house. The spacing of the machines may be fixed by the width of the flume or scroll case at entrance to the runner or draft tube at its mouth, or perhaps by the overall diameter of the alternators. For concrete and steel flumes, the width of the draft tube and tail-race will determine the spacing. Figs. 565 to 571 show typical plant layouts for vertical reaction machines.

Perhaps the most suitable arrangement for horizontal machines is to place them at right angles to the length of the turbine house, the spacing being determined as with vertical units. This layout is most frequently used with open-pit construction for low heads.

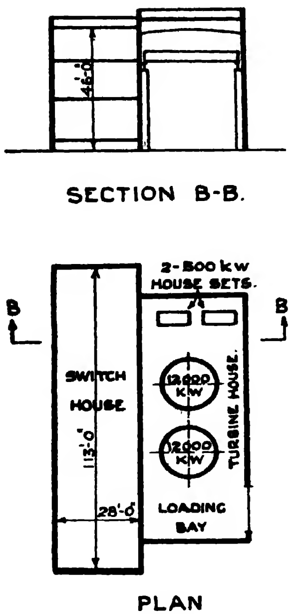

Fig. 566.

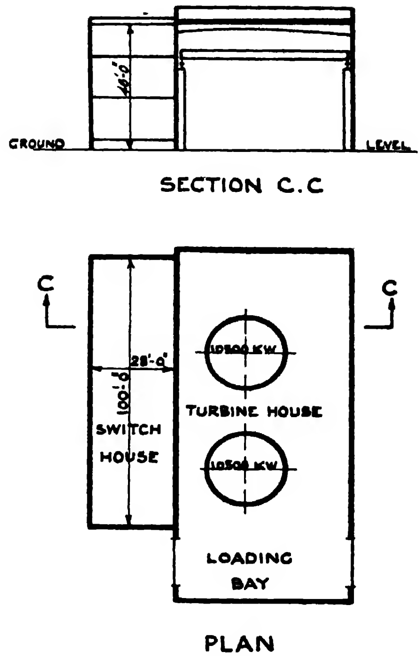

Fig. 567.

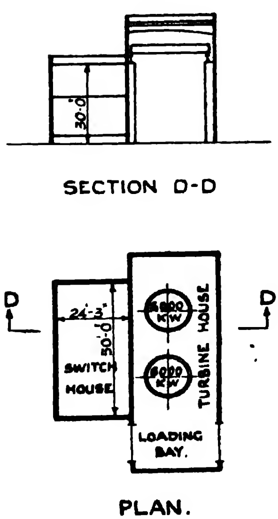

Fig. 568.

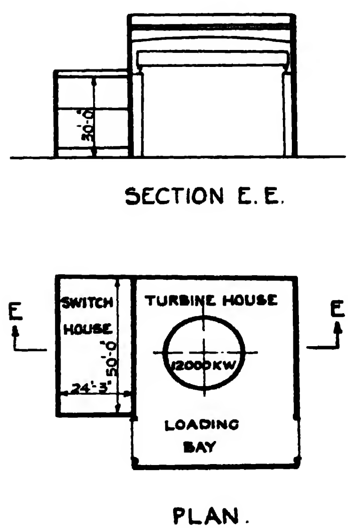

Fig. 569.

Impulse Machines. The horizontal setting is the most usual, with the wheel shaft placed parallel to the longitudinal axis of the turbine house. The spacing is fixed by the dimensions and necessary

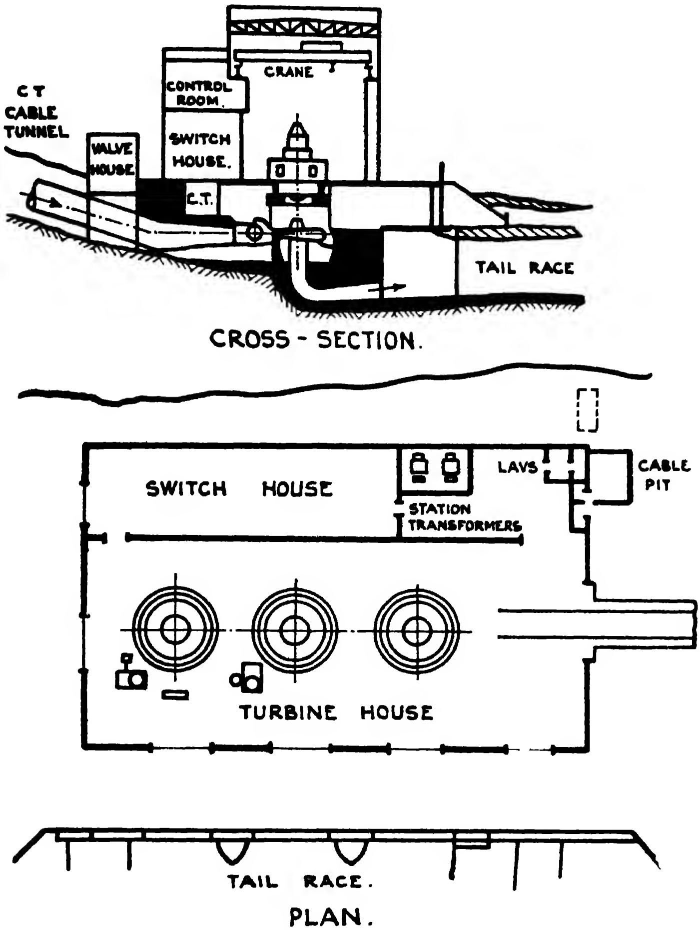

Fig. 570. Layout of Station.

clearances rather than by the penstock, flume or tail-race widths, as the amount of water discharged is relatively small.

Vertical settings with multiple nozzles are rare, but the machines should be arranged with centres on a line parallel to the axis of the turbine house, both penstock and tail-race channel following in the same direction.

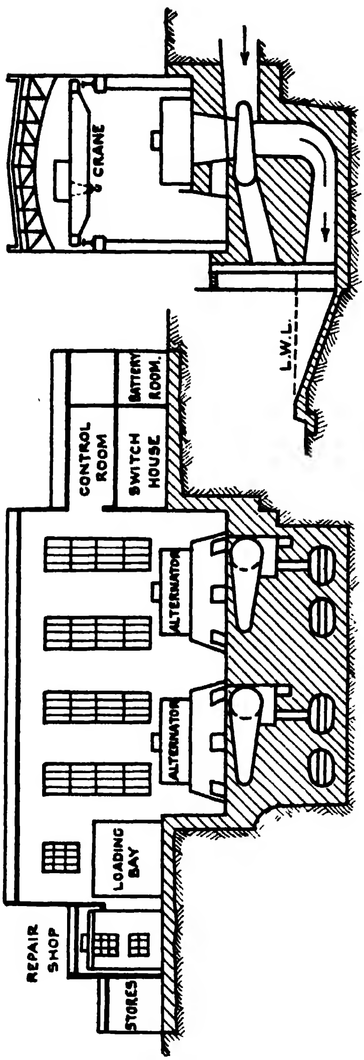

FIG. 571. Sections through Station.

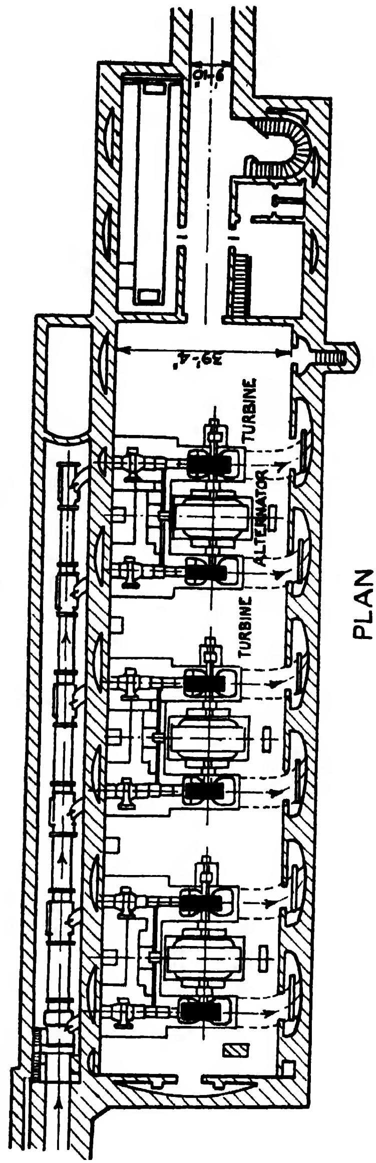

FIG. 2. Italian Underground Station with Double Pelton Wheels.

For horizontal machines arranged with the shafts at right angles to the longitudinal axis of the turbine house, the same conditions govern the spacing. Where the machines have their shafts parallel

with longitudinal axis of the turbine house, the spacing will, subject to any special features, be settled by the length of the wheel and alternator.

A comparison of horizontal and vertical turbines with respect to

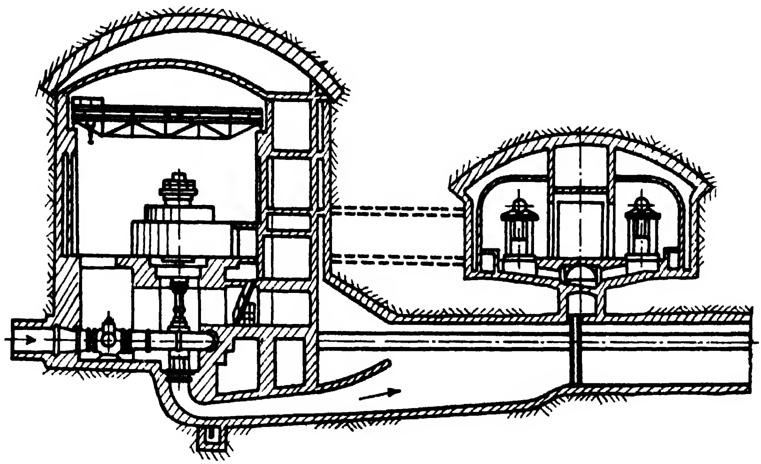

FIG. 573. Italian Underground Station with Vertical Shaft Turbines.

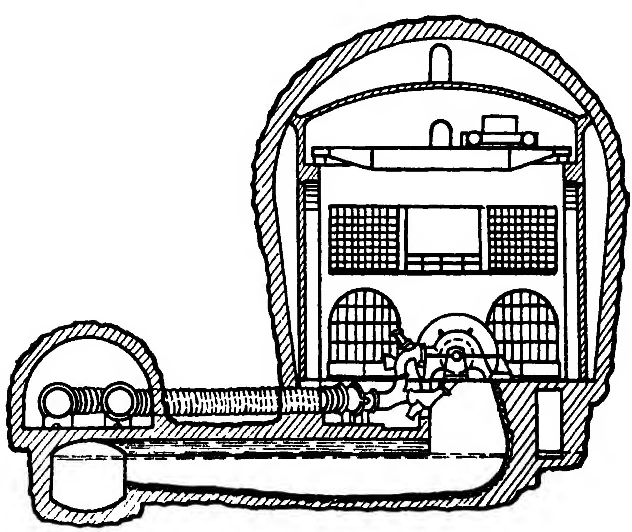

FIG. 574. Italian Underground Station. 220 MW (55 MW each) Pelton Wheel Machines.

building capacity is given in Table 96, which shows the vertical machine to advantage in regard to compactness of station layout.

TABLE 96

Type	Turbine		Turbine House			
	MW	r.p.m.	Area. sq. ft.	Volume cub. ft.	Sq. ft. per kW.	Cub. ft. per kW.
Horizontal . .	15	360	16,000	680,000	1·06	45·2
Vertical . .	15	300	7,000	322,000	0·47	21·4

Turbine house volumes vary from 10 to 80 cub. ft. per kW.

In a number of continental countries many underground plants have been installed, and special layouts have been devised to meet such conditions. The power station itself (Fig. 572) is hewn out of the rock, and contains three sets of Pelton wheel turbines each driving 19·5 MW alternators generating at 10 kV. The station dimensions are 175 ft. long, 50 ft. wide and 49 ft. high.

In Fig. 573 the station is underground in the rock, with a turbine house 234 ft. long, 83·5 ft. wide and 59 ft. high. The plant consists of four 50 MW vertical shaft turbine sets generating at 10 kV. Fig. 574 shows another large underground station.

CIVIL ENGINEERING WORKS AND BUILDINGS

During the preliminary investigations concerning the selection of a particular site, it is necessary to locate the most suitable positions for the various sections of the works, *e.g.*, storage reservoirs, dams, tunnels, pipe-lines, surge tower and power plant buildings. The headworks are where the water first comes in contact with artificial works. It may be necessary to divert a river and carry out considerable preliminary works before setting about the main works associated with a scheme.

Storage Reservoirs. With very high annual load factors, the storage necessary to ensure a continuous output based on average flow, and allowing for rainfall variations, would seldom be economically justifiable. Storage water would only be drawn off at full capacity for short periods, and the capital charges incurred would be exceptionally heavy.

Low fall plants of large capacity require large volumes of water, and to provide adequate storage considerable pondage is required.

The levels and contours of the ground to be used for storage should be investigated, and calculations made to ascertain the actual capacity available. A certain amount of storage capacity is lost due to evaporation and ice formation, the latter being in the ratio of the depth displaced by the ice to the working depth of the basin.

For flood protection alone, detention or retarding reservoirs may be constructed with an outlet conduit at the base of the dam to control the discharge of water.

In some cases dams are so arranged that when desired the water level can be raised by means of temporary flash-boards or permanent collapsing gates, and in this way additional water can be impounded at the end of heavy rainfall or before the close of the rainy season.

A regulating reservoir may fulfil two functions :—serve to augment the water available at times of light load, and act as a reserve against breakdown in the water supply between the reservoir and the headworks. If the supply is plentiful, the first need not be considered, and when the reservoir is situated at the headworks, the second disappears, for failure is more likely to take place in the flume than elsewhere.

If the pipe-lines take off directly from the reservoir, the effective depth of the latter should be small compared with the total head, otherwise the variations of head between full and empty reservoir will affect plant operation.

The principal object is to secure as much storage as possible for a given expenditure. It may be necessary to include a silt trap immediately preceding an artificial reservoir. A natural reservoir formed by a dam, must take care of itself in this respect, unless it is practicable to construct a smaller dam up-stream for use as a silt trap.

An overflow weir to pass surplus water is also essential, and it may be possible to sectionalise the reservoir where muddy water obtains so that a section can be cleaned while the remainder is in use. That portion of the reservoir from which the pipe lines are taken should be isolated from the rest, and supplied with clean water from the top surface by way of screens and gates. Valves should be provided at the bottom of this chamber for use when stored water has to be drawn upon.

Dams. The primary function of a dam is to afford a head of water, but, in addition to this, it also creates storage. It may also be required to assist in forming the intake to the turbines. The principles underlying the design of a dam, in addition to other features, are safety and economy.

In the design and construction of dams it is necessary to seek expert civil engineering and geological advice. Special attention has to be given to such points as :—effecting good joints between the concrete dam and solid rock; elimination of water leakage with its possible underpinning of the dam; the effects of floodwaters, ice-floes, and springs, etc.

The principal types of dam are :—concrete, masonry and earth; although in practice combinations of these are sometimes constructed. The concrete and masonry dams may be of the gravity or solid type, and the arch and buttress types. Concrete and masonry constructions are permanent and require a minimum of upkeep and attendance; they offer the advantages of maximum height, longest life, most economical in water conservation and lowest maintenance charges compared with the ordinary earth dam.

A preliminary survey should first be made of the proposed dam site and its surroundings to ascertain the particular geology and materials available for the construction; the valley gradients; nature and extent of the catchment area or water-shed; probable rate of siltation; the legal position controlling flood storage; existing riparian rights, area affected, etc. Where the strata are broken up by natural convulsions, the impounding of large quantities of water introduces severe stresses, and subsequent percolation may affect wide areas in the vicinity, with unpredictable and possibly disastrous results. An estimate can then be made of the possible economical height of dam, foundations, and construction materials available on site. Good masonry will bear with safety a load equivalent to about 17,500 lb. per cu. ft.; *i.e.*, masonry weighing 125 lb. per cu. ft. has a safe load—height of 17,500/125 = 140 ft. Foundation rock that is moderately hard will bear about 18,000 lb. per sq. ft. Where good appearance is desired, the down stream face may be covered with stone. For stability, the dam may depend on its weight, *e.g.*, gravity type, or the structure may be of the arch type, the convex side facing up-stream. The multiple arch dam consists of a line of buttresses spaced a little distance apart and joined by arches.

Earth dams, with or without a core, have been used, the core

being a central impervious section usually concrete or puddle clay. If adequate and suitable quantities of gravel, sand and clay are available it is possible to make a watertight structure without a core wall. Fig. 575 shows section of an earth dam with a core wall of concrete. The concrete is taken down to rock and the top is carried above the level of the embankment. As a protection against wave action, the up-stream face is pitched with stone. The embankment is built up in layers of not more than one foot thick and with the most impervious materials placed near the centre of the dam. Each layer is thoroughly rammed before continuing

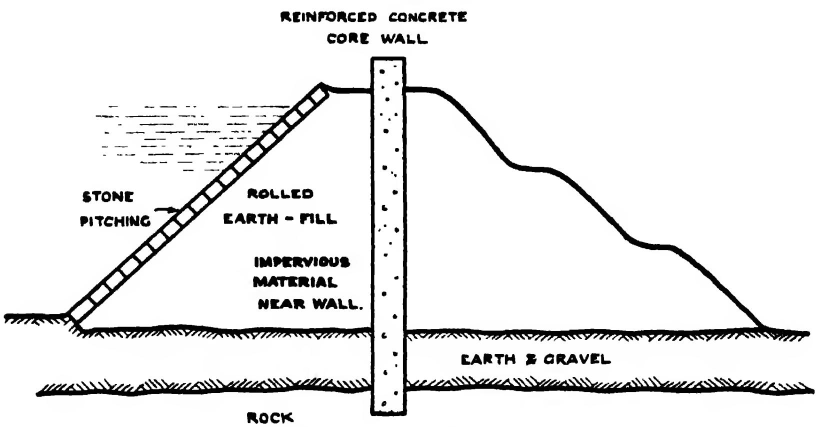

FIG. 575. Earth Dam.

the work. An adequate spillway must be provided at a level well below that of the crest of the dam. Pipes or ducts passing through earth dams, unless very carefully constructed, are likely to give trouble from leakage.

Rock-filled dams consist of an embankment formed of loose pieces of rock and made watertight by a core wall of concrete or a lining of concrete, timber, or steel placed against the up-stream face. They are difficult to make watertight and often require attention.

The force due to impact of flowing water is seldom large in comparison with static pressures. In one case it was found necessary to heighten a gravity dam and for constructional reasons it was essential that the up-stream face of the raised portion of the dam should be vertical. Apart from this, however, an inclined face would have reduced the factor of safety against sliding, as the underlying formation sloped in a down-stream direction.

The principal forces to which dams are subject are:—water pressure; earth pressure; ice pressure; weight of dam; and stresses in masonry.

Other forces acting on a dam may include that caused by air pressure on the spillway section due to partial vacuum forming under the nappe of the water flowing over the dam as a result of imperfect aeration at the ends of the sheet of water. Strong vibrations are set up by the periodic making and breaking of this partial vacuum.

Ice pressures may also have to be allowed for, and the greatest pressures are set up in narrow waters where the ice is confined. A heavy sheet of ice freezing to the dam face followed by a lowering of water can also result in considerable forces on the dam. It has been suggested that vaseline generously applied to a dam prevents adhesion of ice and averts the hazards of its removal. Other conditions also have to be allowed for. An overflow dam, providing it is subject to flow, will not be affected by ice thrust.

A dam may yield by :—

(*a*) Overturning about any horizontal joint.

(*b*) Sliding of one horizontal section over that below it.

(*c*) Crushing of the foundations or of any joint due to excessive compressive stress.

(*d*) Shearing of the material in the plane of maximum shear.

It is recognised that a concrete gravity dam, in spite of its great mass, may have a low factor of safety owing to the deformation of the underlying rock. The influence of this elastic behaviour may be overlooked in the analysis of gravity dam design and result in only average values of stresses being determined. The actual maximum stresses may, on the other hand, be much greater, and those at the down-stream toe of the dam can approach the permissible limit for concrete. A gravity dam, often considered as a plain structure, is actually a structure stressed in three dimensions.

The fundamental principle upon which methods for reducing uplift and leakage in dams are based was realised by earlier continental designers. Apparently the general idea underlying the solution was to subdivide the structural elements into two distinct parts, depending upon the particular functions they were intended to perform; *i.e.*, (*a*) creating a watertight screen, and (*b*) providing the necessary means for supporting this screen in position, so as to render it capable of withstanding the water pressure.

The majority of dams are of reinforced concrete of the arch type, while cut-off dams may be of the concrete gravity type.

Part arched dams are also used, the arched portion depending for its stability on its arch-like construction, the crown being against the head of water and buttressed against the straight parts of the dam on each side which act as abutments. Such a construction effects considerable saving in excavation and in the materials

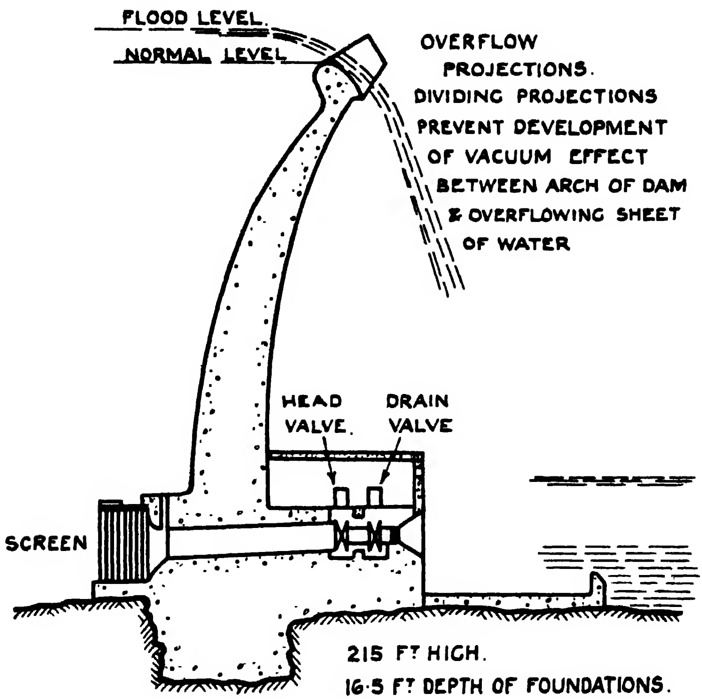

FIG. 576. "Thin Arch" Dam.

used. An arch form of construction with a gravity dam extension enables a spillway and intake structure to be incorporated. Fig. 576 shows one form of "thin arch" type of dam.

The dam is cement rendered and the bottom caulked with clay to prevent leakage. A spillway is usually provided in the dam to clear away loose ice or provide for excess or compensation water, and a salmon pass and perhaps eel passes may also have to be provided. Log passes or chutes are also required in some countries to enable a steady supply of logs to be floated down-stream.

The essentials for the foundation of any dam are that it should be as impervious as possible, and should be such that it will withstand safely the weight imposed upon it and also the tendency to slide or shear. Several test holes may be drilled in the foundation to a depth varying from 10 to 20 ft. and tested with water at 100 p.s.i. in order to disclose any possibility of leakage. Provision is made for grouting these holes, and each site will require special consideration. The topography affects the dimensions, and hence the quantities of materials required in its construction.

Facilities may be required for unwatering a stream or small river by carrying its flow past the site works, and a stream may necessitate coffer-dams.

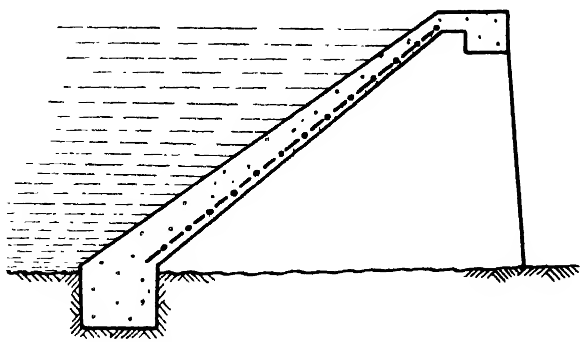

FIG. 577. Buttress Dam.

A buttress dam (Fig. 577), which consists of a line of triangular-shaped buttresses spaced about 20 ft. apart, may be used inclined at an angle of 45 to 50 degrees to the horizontal. Instead of a flat decking, arches may be used to fill the spaces between the buttresses. Arches permit of wider spacing between the buttresses than is permissible with a flat decking. A concrete gravity dam may have a reinforced concrete slab on its up-stream face to prevent any uplifting action. The stability of such a dam is due chiefly to the vertical component of the water pressure on the inclined up-stream face. The pressure on the foundations can be more uniformly distributed, and it can be used on many sites where a gravity dam would not be practicable owing to the poor foundations. The factor of safety against sliding usually determines the down-stream slope of the buttresses, but additional security against sliding can be provided by dentating the contact surfaces of the laminated rock foundation. The spacing of the buttresses is chosen so as to

fit the dam to the ground with the least expenditure of concrete. By varying the angle of the heads and changing the thickness of the buttresses, both the heads and buttresses can be adjusted to correspond with the maximum water pressure. This procedure effects a saving of from 30 to 35 per cent. of concrete on the quantity required for an equivalent gravity dam.

A large amount of material is put into a gravity type dam to provide weight, whereas it is more economical to use water.

The hollow dam is a form of buttress dam, the space under the decking being used to accommodate the generating and other plant. The down-stream face of the dam is also covered with a sloping decking which serves as a spillway. The entire length of the dam can be used for discharging flood-water, and this is useful when it is difficult to obtain adequate spillway space.

In some cases it may be necessary to use a considerable part of the crest for spilling surplus water, and this should cater for the highest possible flood. The profile of this portion of the dam should be designed to give a suitable water path. The down-stream face is curved so that the water will follow it. If the crest is very thin the water may tend to jump clear of the down-stream face, and under these conditions a partial vacuum may be created under the nappe and so increase the overturning force on the dam. At the bottom, the water is directed away from the base of the dam where it may cause erosion and undercutting. The toe of the dam should be carried out in such a way as to divert the water away from the foundations. Some French stations have "ski-jump" flood overflows on the down-stream face of the dam and over the roof of the turbine house. In one case the water from two overflows is projected 165 ft. downstream from the foot of the turbine house in such a way that the jets meet in mid-air before falling down into the river bed. The syphon spillway is a device to use the suction head and thus obtain a high rate of discharge. It is self-starting, the air being driven out when the discharge starts. The theoretical suction head is 34 ft., but the practical maximum is considerably less. In some cases two or more syphons are arranged to come into operation during heavy floods. The syphons are turned upwards at their lower ends to form a seal and so prevent access of air during priming. At the outlet there is a jet disperser to dissipate the energy of the discharging water. Dispersion is also assisted by the seal at the bottom of the syphon.

Straight dams are liable to develop cracks due to contraction

in very cold weather, and precautions should be taken to prevent such happenings, especially in dams of moderate thickness. Temperature cracks may be overcome by adopting curved or arch construction.

For all but small dams it is desirable to include expansion joints at regular intervals throughout the length of the dam. Various types of joints are used, and Fig. 578 shows typical constructional features. In (*a*) the grooves are cast in one end of

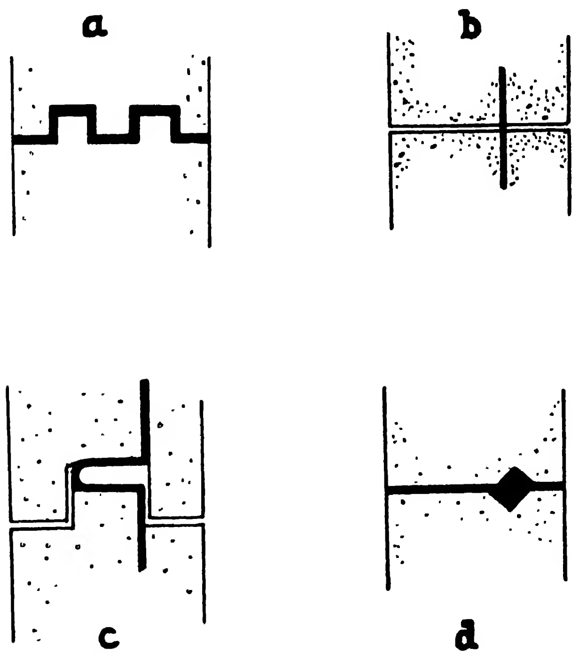

FIG. 578. Expansion Joints.

the section and coated with bituminous paint or pitch ; (*b*) a steel plate is inserted to prevent adhesion of the concrete ; (*c*) the tongue and groove of (*a*) is used with the addition of a bent copper or lead strip ; (*d*) a square or circular groove is moulded from top to bottom of the joint, and this is filled by a dowel of asphalt which may be between 3 and 6 in. diameter. In a dam which was raised, the curtain walls were provided with expansion joints spaced half-way between the centre lines of the buttresses which had been provided. One face of each expansion joint was coated with $\frac{3}{16}$ in. of hot

pitch and tar paper. Each joint had four transverse seals consisting of one rubber strip 9 in. wide by $\frac{3}{8}$ in. thick; one copper strip $11\frac{3}{4}$ in. wide by $\frac{1}{16}$ in. thick, and two $5\frac{1}{2}$ in. square vertical wells which were later filled with hot pitch. The expansion joints extended down to the crest of the old dam.

Maximum temperature conditions obtain when the dam is empty, and expansion joints should be spaced at intervals of not exceeding 100 ft., but for thin dams this figure should be much less. Artificial cooling of the concrete and the use of low-heat types of cements are quite common practice for large gravity dams, in order to produce a monolithic structure without either longitudinal or transverse cracks.

On smaller installations it is usual to provide flash-boards on the crest, which can be adjusted in height to suit water flow. The boards can be loosely attached to iron pins which fit into sockets embedded in the concrete spillway. Adjustable arrangements are also possible. Sector gates and rolling dams are used on large schemes.

Drainage gates with either manual or automatic control must be included at the lowest level for drawing off the water, and they are also useful during the construction period for passing water. Compensation water may have to be allowed for, and fishing rights preserved. Gates are often included to aid in the passage of flood water, but a free and unobstructed spillway is usually the most dependable means of handling this water. It is difficult to handle large floods by gates alone, and the spillway remains the principal means to this end.

As already mentioned, the construction of dams of any size requires great attention to detail. To increase the impermeability of the underlying strata, a comprehensive programme of pressure grouting may be essential. After completion of the excavations and before concreting is started, it is necessary to remove all loose material and then thoroughly clean the rock surfaces by hosing and brushing. To ensure a good bond between the concrete and the rock, it may be desirable to spread a bonding layer of specially rich concrete over the rock surface at the start of concreting. The same procedure is necessary to bond fresh concrete to set surfaces, but before commencing work, the surface skin of the old concrete should be completely removed. Concreting should be done in layers, possibly varying from 2 to 4 ft., and the size of blocks limited to suit specified time periods. To improve the shear strength of the concrete in

the horizontal joints, grooves may be provided in the top of the completed concrete lift, or, alternatively, it may be finished off in a series of slopes with the highest at the down-stream face of the dam. Additional bonding may be obtained by providing stones which project above the top of each lift.

Dams are constructed in bays, these being the full width of the dam, and up to about 50 ft. in length. The intervening spaces are usually about 5 ft. and are left unfilled until the concrete in the bays has aged sufficiently and the majority of the shrinkage has taken place.

During construction of dams various practices obtain, but the following examples are typical :—

In a mass concrete dam 1,066 ft. long and 182 ft. high, the concrete mix consisted of a 7 : 1 ratio of aggregate to cement. A special low-heat Portland cement was used with four grades of aggregates ; 6 in., 3 in., 1½ in., and fines. The concrete was poured in 4-ft. lifts and in blocks about 46-ft. long, each of which stretched across the entire width of the dam ; there were twenty-three blocks in all. An interval of six weeks was allowed between the placing of adjacent blocks, which enabled contraction of the original block to take place. Subsequent contraction of the adjacent block formed a transverse vertical joint sufficiently large to accommodate thermal movements in the completed structure. A corrugated vertical strip of copper was placed along each of these joints near the up-stream face of the dam to ensure permeability.

Another dam was raised to provide increased storage, and it was the practice at the end of a day's run to leave the surface on a slope of about 5 : 1, with the high part at the down-stream end, and leave keys in the sloping surface. Before fresh concrete was placed on the hardened surface, this was roughened and then cleaned by compressed air and a water jet, and slushed with cement mortar.

The construction of one dam was complicated by the fact that one bank of the river at one point consisted of permeable gravel. To prevent leakage of water, an impermeable clay bank, protected by rock fill, was constructed.

The use of granulated slag (steelworks) cement saves coal during preparation and the effects of contraction are much reduced. There is a reduction in the rise of temperature of the concrete mass which only reaches 104° F., whereas Portland cement would approach 144° F. In any case the concrete is usually cooled by a system of tubes with cold water circulation.

Dam Crest Gates. Lifting dams may be used where conditions are suitable to give very considerable heads, but capital cost is usually the deciding factor. The spillway in the centre of a dam may have three or more openings, each fitted with a gate, to enable the water level to be raised and increase the storage. Gates of various designs are used, *e.g.*, vertical roller-bearing type, and rolling type.

In one dam with four openings, three had Taintor gates to control water level, and the fourth, for floating logs, had a submersible sector gate.

Canals. The object of the canal or channel is to convey the desired quantity of water to the forebay with as little loss of head as possible. The slope should be gradual so that the loss of head is small. When the ground is almost impervious and the velocity of water is low, an inclined channel may be used.

The trapezoidal or semicircular shape will generally be the most suitable as this gives a larger hydraulic mean depth than a rectangular one of the same area. The friction head loss is increased by all bends in the direction of flow, and either the area or the slope should be increased accordingly, and the flow calculated.

In low-head plants the water is taken to the turbine in an open-head race in which the velocity is kept as low as possible, about 2 ft. per second, to reduce friction and eddy losses. Typical values are:—

Ordinary velocity allowable . .	2–3 ft. per sec.
Velocity in sand	1 ft. per sec.
Velocity in hard gravel or clay .	4–6 ft. per sec.

Too low a velocity is not altogether desirable in earth-lined canals, as there is a tendency to deposit silt and precipitate the growth of weeds and other aquatic vegetation.

Canals may be lined or unlined, and local conditions usually determine the type to be used. For high velocities of flow, the channel should be lined with stone pitching or concrete to prevent erosion. The loss due to seepage can be considerable where the soil is very pervious.

A concrete lining varying from 3 to 6 in. is quite suitable, and although the cost of lined canals is higher, there is a saving on maintenance and cleaning, and the capacity is increased. Stone paving is also used as a lining material. There is a loss of capacity due to ice cover which may have to be allowed for.

If the quantity of water is considerable, an earthwork canal

will be used, puddled or lined should the ground render it necessary. The water is taken to a forebay to which the pipe-lines are connected, and it is at this point that the supply is controlled by valves or gates. An overflow and scour are also required, but as a rule silt traps will not be necessary. Overflowing should be provided for by the inclusion of suitable spillways.

A coarse trash rack is placed at the intake to protect the channel, and a strainer in the forebay, close to the gate, to protect the turbines.

In one scheme an aqueduct commences at the intake dam and terminates at the forebay above the power station. It is trapezoid in section, the sides and bottom being formed of reinforced concrete placed *in situ* with contraction joints. At the forebay a further set of screens is provided, together with two square gates each controlling the entrance to one pipe.

If a canal is emptied for repair, water pressure may be set up behind a concrete lining unless suitable drainage arrangements are included. In one plant the waters from the tunnels surface into an open-cut canal after a series of bends has reduced their turbulence. Before reaching the forebay of the station the canal can make an × cross-over with an existing canal to an adjoining station at which the waters are redistributed.

Forebay. The forebay or intake, comprises all the works for drawing the water from the reservoir or river, and feeding it to the canal and pipe-lines. Its function is to supply water to meet the hour-to-hour demands on the station. The larger the capacity of the forebay, the easier is the operation of the station, because there is adequate water and storage capacity to meet all possible load fluctuations. The intake works, shown in Fig. 579, are placed with special regard to ice difficulties. Cake ice in large quantities is carried down for weeks at a time, and a long tapering forebay, the entrance to which is protected by the main intake, terminates in a deep spillway. The intake, 600 ft. long, is almost parallel with the river flow, and a concrete curtain wall extends 9 ft. into the water which is 15 ft. deep at this point. The gate openings beneath the curtain admit only deep water, and this only at right angles to the swiftly flowing surface water, which carries off the pack ice to the rapids beyond. A similar arrangement follows at the screens, and the water is 30 ft. deep at the gate house. Both screen house and gate house are heated by steam supplied from an underground boiler plant located in the common abutment. The water to the

tunnels has to pass in succession three steps, 1, 2 and 3, each excluding surface water and floating ice, and through screens. Electric cranes are provided for lifting the latter and for cleaning and changing.

Even when the pipe-lines lead off directly from a reservoir, a section of the latter is usually isolated to act as a forebay for protection and control of the pipe-line intakes.

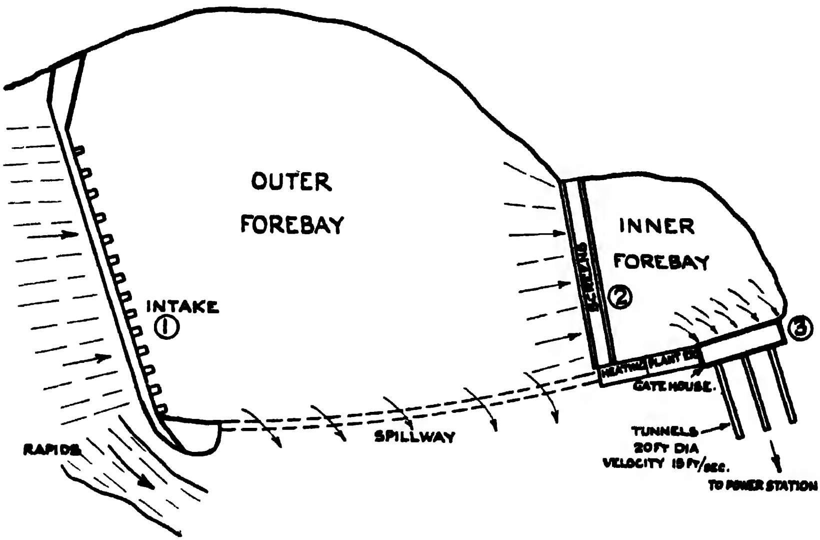

FIG. 579. Intakes for a Large Plant.

If an open-channel is used, the forebay also serves as a small balancing tank to even out fluctuations in load. The capacity is usually sufficient to carry the turbines over the period required for the water to flow along the channel. Sometimes the forebay can be arranged along the contour in the form of an enlarged channel, but the cost of the constructional works is greater than that of a circular pond. A spillway is provided to allow excess water to escape. The spillway may be either at the forebay itself or at the most convenient outlet farther up the channel, if the levels allow this to be done. It is usual to have a separate chamber for each pipe, controlled by gates and screens, but open to the air at the top. This ensures that under no circumstances can a pipe-line collapse from external air pressure, and it also facilitates repairs and maintenance.

In fixing the capacity of the forebay some care is required, particularly where any length of canal intervenes. The canal is maintained full, and the spillway at the forebay allows any surplus water to pass over it. Should it be necessary to economise in water, then regulation of water flow can be arranged for at the canal intake. Sufficient water should always be maintained in the forebay to enable a sudden rise of load to be handled until such a time as the canal flow can be increased. The site should be chosen with care, and the angle of its intake with respect to the direction of flow should be arranged in such a way as to avoid the accumulation of debris. If possible, the opening should be almost at right angles to the flow. A log-boom helps to keep floating debris and ice away from the opening.

Screens. These are provided to prevent logs, fish and other obstructive elements from entering the pipe-lines and turbines. The spacing of the bars in the racks should be such that anything passing will pass through the turbines. For the coarse racks a series of flat iron bars on edge. 3-in. pitch and 3 in. deep by $\frac{3}{8}$-in. thick, is suitable. The actual spacing depends largely on the floating and suspended matter obtaining but in general should not exceed 4 in. The following are typical spacings for vertical racks :—

Where used	Space between bars
Impulse turbines	20–25 per cent. of nozzle diameter.
Racks in front of long pipe-lines .	$\frac{3}{4}$ in.
Medium output Francis and Kaplan turbines	2–3 in.
Large output Kaplin turbines . .	3–6 in.

$$\text{The head loss} = k \,.\, \sin \alpha \,.\, \frac{1{\cdot}33 \,.\, d \,.\, V^2}{2g \,.\, a} \text{ ft.}$$

where k—flow coefficient which varies from 2·4 for rectangular bar and 1·8 for circular bar to 0·75 for a streamlined section.

d—maximum width of bar, in.

a—space between bars, in.

V—water velocity up-stream from rack, ft./sec.

α—angle between rack and direction of flow, degrees.

g—acceleration due to gravity.

For a high head plant with pipe-line a mesh rack is often preferable. The bars are built up in sections for convenience in placing, and should be securely supported so as to withstand the

pressure set up due to choking. The area of the water-way is increased by placing at an angle of about 15 to 30 degrees to the vertical, and cleaning by raking is facilitated. Separate racks are to be preferred for each opening so that one may be replaced without affecting the operation of the remainder. Duplex racks could also be used to achieve this object, only one rack being in service at a time at each intake. The racks in the forebay are usually of a finer (1 in. pitch) pitch than those at the main intakes, in order to catch any small debris, such as leaves, etc.

Mechanical raking is often employed on larger trash racks, and strainers or rotating screens for the finer debris. The net rack waterway area should be such that there is no undue loss of head. This loss of head is due to sudden contraction of the rack area and sudden enlargement beyond the rack area. A velocity of flow through the rack of from 1 to 3 ft. per second is usual.

The top of the racks should be placed above high-water level in the canal or gate house, with a trough to carry off the debris down-stream, or to a waste pit which can be flushed into the river.

The possibility of choking of the racks by ice should not be overlooked. A very slight increase in temperature of the racks and water passages will permit free passage. Where large machines are installed, the racks or sections thereof can be lifted to allow the ice to pass through the runners. Compressed air emitted from pipes laid in front of the gates at sill level also help. A steam boiler heating plant is useful for the gate house.

An intake tunnel may be so arranged that water is always drawn off below the surface to prevent driftwood, etc., reaching the screens. The screens are in duplicate, one always being in position while the other is cleaned.

Tunnels. There are two types—pressure type and non-pressure type. The latter serves as a channel, whereas the former enables the fall to be utilised for power production. Pressure tunnels are usually lined to prevent leakage and reduce the friction losses. Tunnels are very costly, and for very high heads a steel lining is frequently included. Concrete lining is also quite suitable, and the friction losses and leakage are reduced.

A circular section has a higher hydraulic efficiency, but a horseshoe section is more easily excavated unless a tunnel boring machine is employed. Solid rock with little ground water is best for tunnel construction. Excavation is usually carried out from both ends, from an adit driven horizontally into hill.

One scheme has a tunnel having a cross-sectional area of 120 sq. ft. and is designed to carry a maximum of 1,440 cu. ft. per second, which corresponds to a water velocity of 12 ft. per second. The section is horse-shoe shaped, and is lined with concrete to present a smooth surface and so reduce frictional resistance. The concrete was mixed in a travelling mixer and pumped into position.

In one station the operators observed an increase in plant output for a few hours after the tunnel had been drained. The tunnel is partly lined with a broken rock roof, as it was not intended to utilise full flow conditions. Apparently the entrapped air

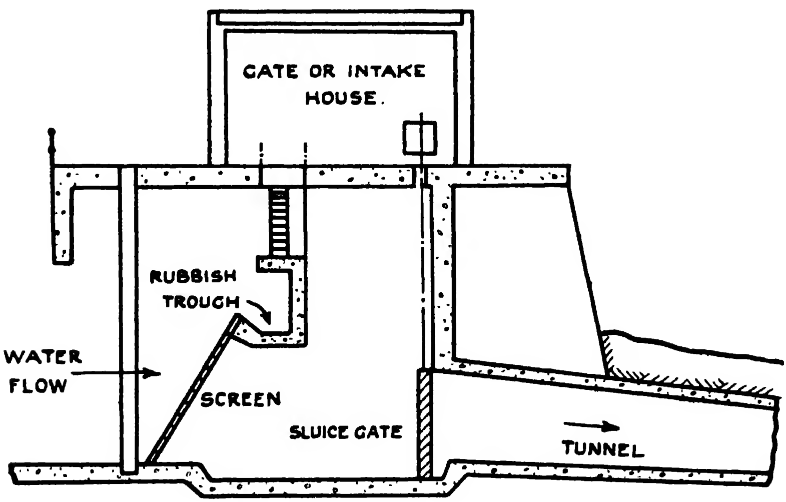

Fig. 580. Gate House Layout.

reduced the friction of the irregular tunnel roof surface. The generated output can be increased some 15 per cent. during high-water months by forcing air into the tunnel to reduce roof friction. Two 40 B.H.P. motor-driven blowers are used for this purpose.

Head Gates, or Intakes. A sluice gate (Figs. 580 and 581) is placed across the pipe-line or tunnel entrance in the forebay, or reservoir, to enable the line to be unwatered or to stop flow in an emergency.

Where large volumes of water have to be dealt with, a number of intake gates are placed side by side. By-pass gates or openings are included to equalise the level on both sides of the main gates to facilitate opening. A rectangular intake can be provided for

each pipe-line and shaped to give a good streamlined flow. The crest should be well above the foot of the intake screens, so that the heavier debris cannot be carried into the pipe-line.

The water seal at the intake varies with the size of pipe-line and the water velocity, and if the depth of cover is too small, whirl-

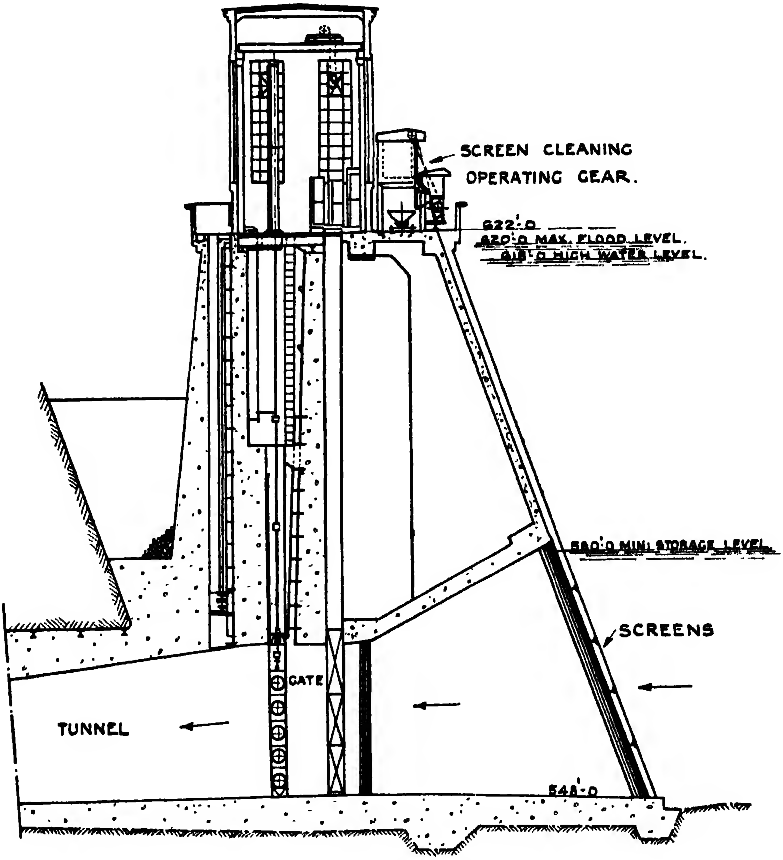

FIG. 581. Intake House Layout.

pools will tend to be set up and carry air into the line and turbines, and thus tend to reduce the output.

An air vent or stand-pipe should be placed immediately below the gate and connected to the top of the pipe-line, and taken to a level above the head water. This enables air to enter when the head gates are closed and water is drawn off through the turbines,

and so prevents the setting up of a dangerous collapsing pressure in the pipe-line. A vacuum can be created by—breaking the water column in the pipe-line caused by the shutting of a valve; sudden change in load on turbines; by the bursting of a pipe, or failure at the turbines.

If the water is taken directly into the pipe-line, a sluice valve, either manually or power operated, will serve to control the flow. These gates or valves can be provided with an automatic trip device to close them in the event of the water velocity in the pipe-line becoming excessive owing to a burst.

Suitable drainage arrangements should be included in the intake and forebay. The gates should be arranged to avoid unnecessary loss of head due to sudden changes in velocity.

Stainless steel ropes are almost corrosion free for sluice gate service. In one station the river water with a *p*H value of 6·7 appeared to be responsible for steelwork corrosion troubles.

The up-stream and down-stream ends of the intervening piers should be rounded or formed as a cutwater to maintain smooth stream flow lines. The piers and abutments should have vertical grooves for stop logs to enable the gates to be unwatered for repairs.

The velocity of flow at the gates varies between 0·05 to 0·1 $\sqrt{2\,g\,.\,h}$.

Transformer cooling water may be discharged at the head gates to prevent icing or freezing.

Pipe-lines. From the dam or forebay the water is conveyed to the turbines by way of pipe-lines. These should follow the best and easiest route with a view to fixing the pipes as cheaply as possible, avoiding land slides and providing for the construction of relief ways, etc.

Should there be an intervening mountain or hill, a tunnel will be necessary for a portion of the route. Riveted steel pipes are used for low pressure portions, *i.e.*, nearest the dam, but where the gradient is steeper and the pressure higher, steel pipes with flanged joints are employed, with solid drawn, weldless, pipes for very high heads. Banded steel pipes have been used for heads of about 6,000 ft., together with cast steel bends and valves. Reinforced concrete pipes may also be used for heads of less than 60 ft., especially in cold climates where alternate freezing and thawing tend to cause concrete under high water pressure to deteriorate rapidly. Reinforced concrete aqueducts have been used for low-head work up to 80 ft., as they are better than canals. Head losses are reduced,

ingress of leaves avoided, and maintenance charges are lower. They can be covered with soil and so minimise expansion and contraction due to temperature changes, and the appearance is improved.

Pre-stressed concrete pipes have been used and the advantages claimed are :—safety ; resistance to internal pressure and vacuum, also lengthwise and crosswise deflections ; resistance to corrosion ; adaptability to temperature changes and overall flexibility of pipe-line. In one installation the pipe dimensions are as follows :—external dia. 5 ft. $11\frac{21}{32}$ in., length 19 ft. 8 in., internal diameters varied from 5 ft. 3 in./4 ft. 10 in., working pressure up to 500 p.s.i. Each end of the pipe is provided with jointing rims of cast iron for lower pressures and of steel rims for higher pressure. Test pressures of from 250 to 860 p.s.i. were applied.

The jointing of any two pre-stressed concrete pipes is by the usual spigot and socket joints with rubber gaskets.

Wood-stave pipes are popular in the U.S.A. and Canada, the staves being from 6 to 8 in. broad and having concentric circular faces and radial edges. The staves are placed longitudinally and held in position by circumferential steel bands or rods connected by iron shoes or steel wires wound continuously round the pipe. The stresses are taken by the steel, and the wood serves as a shell. The pipe-line is continuous and the staves are so arranged that the circumferential joints are staggered. These are made watertight by thin metal plates, which are fixed into grooves in abutting faces. The friction loss is low, and material is light to transport and easy to erect. Repairs are easy to carry out, also the pipes are cheap and can be constructed in large diameters and used on heads approaching 250 ft.

Suitably arranged solid anchor supports are placed throughout the length of the pipe-line. Sluice gates or valves are included to isolate the pipe-lines for inspection and maintenance, and in cold climates heating elements are provided in the guides to prevent freezing up. Valves and gates may have remote control fitted and be interlocked with a relief valve to permit of rapid discharge in emergency.

The velocity of water in a pipe-line, if short and on a moderate head, may be as high as $0{\cdot}1\sqrt{2g\,.\,h}$, giving 3·6 ft. per second for 20 ft., and 7·2 ft. per second for 80 ft.

The size of the pipes and the loss of head in them under different conditions affect the velocities.

A 12 ft. diameter pipe-line on a head of 50 ft. collapsed inwards; the water had been emptied through the draft tube when the head-gate was closed, so that practically full atmospheric pressure acted upon the upper part. The pipe was capable of withstanding the internal water pressure, but this contingency had been overlooked. The profile of a pipe-line is frequently such that the lower portion has a much steeper slope than the remainder. If a heavy load is suddenly put on the turbines, the water flow in the lower section of the line may accelerate much quicker than that in the upper section, and there will be a tendency to separate at the change in gradient. Such a condition may subject the upper section to collapsing forces, which can be eliminated by including a surge tower at or near the change in route. An alternative is to fit an air inlet valve and so prevent the setting up of a vacuum. This valve is fitted on the top of the pipe and is normally held in the closed position by the water pressure, or by a spring. The valve (Fig. 582) is entirely automatic in operation and almost immune from "freezing." It opens and admits air to break the slightest vacuum, and closes as soon as the pressure in the pipe rises above that of the atmosphere. Air outlet valves are required at the highest point of the line to free air when filling, and also on the down-stream side of the turbine valve when casing is filling.

If the pipe is above the hydraulic gradient line at any point, the pressure will be less than atmospheric. To prevent differences arising from liberation of, and accumulation of, air at such points, and from admission of air at leaky joints, the greatest height above the gradient line should not exceed 20 ft. Owing to the weakness of large pipes under external pressures, they should not be laid above the gradient line.

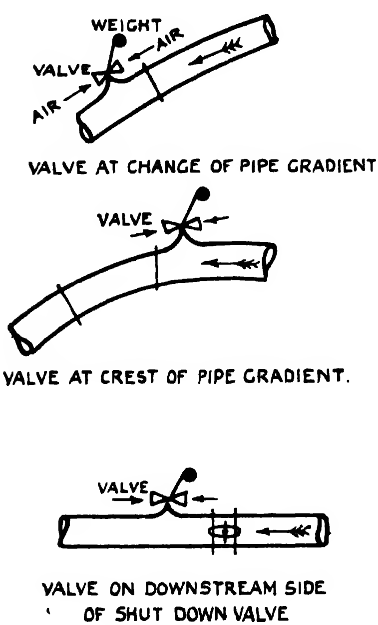

Fig. 582. Anti-Vacuum Valves in Pipe Lines.

Each pipe should have its own intake chamber and screens shut off from the forebay gates.

Automatic controls are provided by means of which the gates can be tripped and closed from the power station in the event of a break in the pipe-lines. If automatic valves are used at the top of the pipes themselves, an air inlet is provided so that the upper and lighter pipes will not collapse under the vacuum formed as the water drains off.

A single pipe may carry the full supply to the turbine house where branches are taken off a header to the individual machines. The best arrangement is to make each machine a self-contained unit with its own pipe-line. Alternatively, a number of pipes may be installed and interconnected by means of isolating valves to facilitate inspection and maintenance. The inlet valve to each turbine may be controlled by hydraulically-operated rotary valve. This valve is normally in an open position and gives an unobstructed passage for the water and, consequently, reduced frictional resistance. The valve is arranged to close should the velocity of the water exceed a predetermined limit, and can also be electrically-operated from the control room.

A pipe-line may be of uniform internal diameter throughout its length, or it may be graduated, the lower sections being smaller and the upper of larger size than the average required. With very high heads, the latter arrangement enables pipes of reduced thickness to be used where the pressure is greatest.

The static pressure is that corresponding to a column of water of the same vertical height, whether the actual pipe-line be long or short. The pressure is reduced when the water is flowing, but it may be subject to a large increase if the flow is suddenly stopped. The route of the pipe-line must be surveyed, and the exact lie and angle of all bends determined, for errors add to the difficulty of erection. Where the pipe diameter changes, it is usual to fit taper pipes.

At all changes of direction, either horizontal or vertical, of the pipe-line, forces are set up which tend to move the pipes. To counteract upward forces the pipe is anchored to a block by means of saddles and reinforcing bars. Where exceptionally large forces obtain, the more usual concrete base or pedestal anchorage are not altogether ideal. An alternative is to carry the pipe-line on intermediate roller supports spaced at suitable intervals, which also effects considerable savings in anchorages. An expansion joint of the stuffing box or other type is usually provided below each anchorage.

Thrust blocks are required to take hydraulic thrusts and the weight of the pipe, the pipes being securely anchored to concrete blocks at these points to prevent any loads being transmitted to the turbines.

The principal forces acting upon an anchorage at a horizontal bend are :—

(*a*) Dynamic pressure of the flowing water in changing direction at the bend and acting outward from the bend.

(*b*) Resultant of the static pressure on the up-stream section and on the down-stream end section of the bend and acting outward.

(*c*) If expansion joints are some distance from the bend in each direction there will be at times a resultant outward pressure at the bend due to temperature stress in the pipe.

(*d*) On a steep slope the weight of the pipe both above and below the anchorage may produce components of outward force at the anchorage sufficient to require consideration. On a long steep slope, where the pipe is straight, anchorages will also be required to hold the pipe at regular intervals.

The following example shows the approach to the calculation of such forces :—

A pipe 6 ft. in diameter ; heat at bend 50 ft. ; velocity of water 6 ft. per second ; maximum discharge 180 cu. ft. per second :—

$$\text{Dynamic pressure, } P_1 = \frac{180 \,.\, 62{\cdot}5 \,.\, 4{\cdot}6}{32{\cdot}2}$$
$$= 1{,}600 \text{ lb.}$$

Cross-sectional area of 6 ft. dia. pipe $= 28{\cdot}2$ ft.^{2}

Static pressure, $p = 28{\cdot}2 \,.\, 62{\cdot}5 \,.\, 50$
$= 88{,}000$ lb.

From force diagram (Fig. 583), $P_2 = 67{,}000$ lb.

$$\text{Total outward force} = P_1 + P_2 = 1{,}600 + 67{,}000 = 68{,}600 \text{ lb.}$$

$$\text{Concrete required} = \frac{68{,}600}{27 \,.\, 130 \,.\, 0{\cdot}5} = 39 \text{ yards}^3$$

0·5—coefficient of friction of sliding.

Resultant pressure approximately at the outer third.

$$\text{Loading on foundation} = \frac{68}{150} = 0{\cdot}45 \text{ tons/ft.}^2$$

$$\text{Maximum loading} = 1{\cdot}0 \text{ ton/ft.}^2 \text{ approx.}$$

Expansion pipes may sometimes be necessary, but if the line departs from the straight to any considerable extent, expansion can usually take place laterally. Expansion joints are provided between pipe anchorages to deal with expansion and contraction due to temperature changes. Covering the pipes and maintaining them full of water reduces expansion to almost zero.

On very high heads, it is the practice to include air-cushions at certain positions in the line to reduce the shock when the velocity

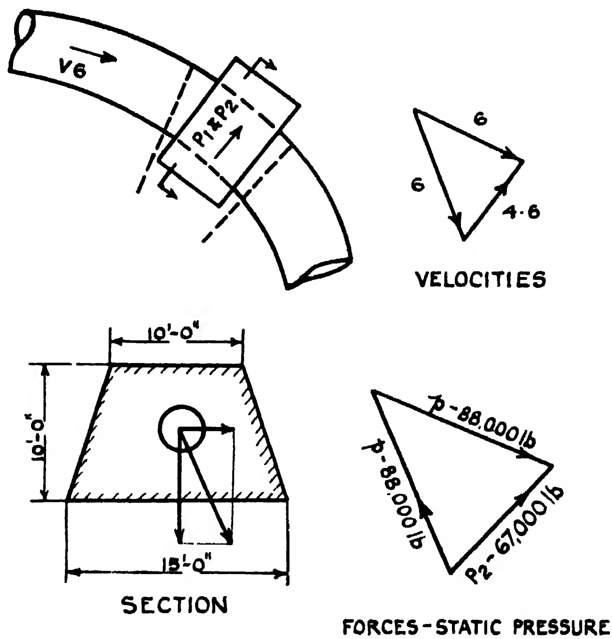

FIG. 583. Velocity and Force Diagrams.

changes. By fitting two vessels side by side, with suitable cocks, the water pressure can be used to force air into the cushion chamber, or a pump can be used.

Plain slip joints and collar-and-sleeve lead joints are suitable for low heads. A flanged joint with a rubber or copper ring between the faces is satisfactory for heads up to 500 ft. or higher. The flanges, which are riveted to the pipes, should be pressed out of steel plate. Cast iron flanges are unreliable when subject to shocks. "Muff" joints depend on a wedge action for keeping tight, and

are to some extent self-adjusting both as to direction and expansion and contraction.

Electrically welded pipes are best and eliminate joints. The piping can be built up of electrically welded rings, and a fabricating shop may be erected on site to simplify the moving of the completed fabricated rings to the assembly position. In one case where $\frac{1}{2}$-in. steel plate was used, each ring had an average length of 4 ft. 3 in., with $\frac{7}{8}$-in. thick flanges on each end to serve the dual purpose of joint rings and stiffeners.

The loss of head increases considerably as the pipes become encrusted, and the velocity of flow varies between 3 to 4 ft. per second for ordinary pipes, reaching a maximum of 7 ft. per second in the smallest section of a graduated pipe-line. Maximum values for moderate heads vary, and figures of 10 to 15 ft. per second and higher have been adopted. In general, a lower velocity is adopted for low head than for high head schemes.

Speed regulation or control of turbines is more difficult with high velocities. The length of pipe-line is also a factor affecting velocity, and where it is reasonably short, high velocities are allowable. In a plant supplied by a long pipe-line under high head, considerations of speed regulation will often be most important. Where the head is moderate and a stand-pipe can be used, the friction loss will be the most important factor.

$$\text{Loss of head } h_1 = \frac{v^2 \, . \, 4\,m \, . \, l}{2\,g \, . \, d}$$

v = velocity, ft. per sec.
l = length, ft.
d = internal diameter, ft.
m = coefficient of friction.
g = acceleration due to gravity (32·2).

The entrance to the pipe-line should be flared to prevent any loss of head due to sudden contraction.

The best pipe size is that where the annual cost (pipe plus value of power lost in friction) is a minimum, the second factor being taken at average load. In other words, the most economical pipe-line is one in which the sum of the annual charges due to interest, maintenance, depreciation, and the value of the power lost per annum in friction, is a minimum. There should be no sudden changes in cross-sectional area of pipe, and bends should be avoided wherever possible.

"m" varies considerably :—

Pipe diameter in.	"m" Clean	"m" Dirty
6	0·007	0·011
36	0·004	0·005

An incrustation or "furring up" almost invariably occurs, and it is usual to make provision not only in respect of allowing additional diameter, but also with a view to removing the scale so formed.

A turbine-type cleaner which is inserted at the top and then driven down the pipe by admitting a limited amount of water can be used. A ball of straw of requisite diameter encircled with steel barbed wire may also prove effective in removing pipeline deposits. It is advisable to provide a chamber of larger diameter than the pipe at all bends with an isolating valve immediately beyond it. A scour pipe and valve above this main valve enables the water and scale to be discharged and the cleaner adjusted for the next section.

The thickness of the pipe can be calculated from the formula :

$$t = \frac{p \,.\, r}{f}$$

p = static pressure lb. per sq. in. = $0{\cdot}433\,h$.

$$= \sqrt{\frac{\text{cusecs.} \times 45{\cdot}8}{v}}$$

r = internal radius of pipe, in.
f = working stress, p.s.i.
v = velocity, ft. per sec.

The ultimate strength of steel is 25 to 30 tons per sq. in. The working stress is about 9,800 p.s.i. for riveted pipes, and up to 14,000 for welded steel pipes.

This assumes a factor of safety of 4.

$$f = \frac{25 \,.\, 2{,}240 \,.\, 0{\cdot}7}{4} = 9{,}800.$$

Efficiency of riveted joints 70 per cent. Minimum $\frac{1}{8}$ in. to allow for atmospheric deterioration or damage from falling stones, etc.

Adequate factor of safety is required to allow for accidental water hammer effects in addition to the normal designed pressure

rises. In practice, pressures up to twice that of the static head, are quite possible.

If H_R = pressure rise, ft.
L = length of pipe-line, ft. (1,000 ft.).
V = velocity of water before gate starts to close, ft. per sec. (10 ft. per sec.).
T = total time of governor closing, sec. (6 sec.).
G = acceleration due to gravity, 32·2 ft. per sec.^{2}

then $H_R = \frac{2\,L\,V}{G\,T}$ approx., substituting figures for example,

$$H_R = \frac{2 \,.\, 1{,}000 \,.\, 10}{32{\cdot}2 \,.\, 6} = 103 \text{ ft. rise for a plant}$$

with a static head of 100 ft.

In general it has been stated that if the pipe-line length is not more than three times the height of the fall, the pressure changes, due to the action of the governor, are not sufficient to be dangerous or seriously affect governing. The theoretical maximum possible additional pressure in lb. per sq. in., due to stopping the flow instantaneously is 63·5 times the velocity in ft. per sec.

Valves are required for safety and dismantling purposes. For low heads, either butterfly or sluice valves are normally used, but for high heads some form of balanced stream-lined valve is required. They may be arranged for hand, electrical or hydraulic operation, and it should be impossible to close them too quickly and so set up water hammer.

The advantages of an exposed pipe-line are :—cheaper—due to considerable reduction in excavation work ; more accessible for construction and subsequent repairs ; less deterioration and usually longer life.

On the other hand, there are certain advantages in coverings : free from dangers of snow, rock and earth slides ; fewer expansion joints required ; little or no supporting arrangements, and there is less possibility of ice formation internally during exceptionally cold weather. Pipes are sometimes embedded in concrete, especially in the dams, and this enables the use of a smaller thickness of metal. They can be stiffened by means of continuous angle reinforcements attached round their periphery, thereby strengthening them against inward pressure caused by any infiltration through the dam.

The painting of exposed pipes requires care, and in practice it is found that a coating mixture of pitch, coal-tar (naphtha removed)

and oil is suitable. Whatever material be used it should give a smooth finish, be tough and tenacious when cold, and not be brittle nor have a tendency to peel off. After erection, the interior of a pipe-line is scraped, and a rust-preventing solution applied cold and then given a final covering of bitumastic enamel applied hot. Bituminous paint has proved quite satisfactory. As a protection against corrosion pipes can be shot-blasted and sprayed with 0·003 in. of zinc, followed by 0·003 in. of aluminium, and finally painted with three coats of bitumastic paint.

Steel pipes are given a coat of linseed oil or some clean primer before despatch to site, to afford protection against rust during transit. Red lead, graphite, and other paints have all been used. Where the pipe-lines are exposed within the power house for considerable lengths, two coats of granulated cork covering may be applied to the outside of the pipes. This prevents moisture forming due to condensation.

In one 24 MW station, mild steel pipes (Fig. 584) were used, and a static head of 410 ft., with a maximum working head of 500 ft., were allowed for. The ultimate tensile strength is 64,000 p.s.i., and maximum working strength in full plate 13,500 p.s.i. after a deduction of $\frac{1}{8}$-in. had been made for corrosion allowance. To ensure rigidity, the minimum thickness of plate is $\frac{1}{2}$-in., and the pipes were supplied in 24 ft. lengths made up in three sections electrically welded together. An external cover strap was provided for the welded longitudinal joints. For circumferential joints, which were made on site, riveting was employed, the butt joints between the pipes being welded on the inside and the cover straps caulked externally. Erection of the pipe-line started at the bottom and progressed upwards, and by means of a rope and inclined track the pipes were drawn uphill and placed in position. Before leaving the maker's works, all pipes were tested to a pressure of 50 per cent. above maximum working pressure appropriate to their position. The completed pipe-line was subjected to a pressure which was equivalent to 23 per cent. above the maximum working pressure at the bottom, and about 75 per cent. in excess at the upper end.

On one pipeline the upper part of the pipe is of steel the wall thickness increasing progressively and the lower part of the line is made from chromium-copper alloy, the wall thickness also increasing towards the station inlet. The pipe lengths were welded in position on site, the longitudinal seams being shop welded. The site welds

were heat-treated with a gas flame to relieve any internal stresses and the pipes were immediately embedded in concrete with a wire-mesh reinforcement. There are no expansion joints in the pipe, which is anchored in three concrete blocks, one at each end and the third in the centre.

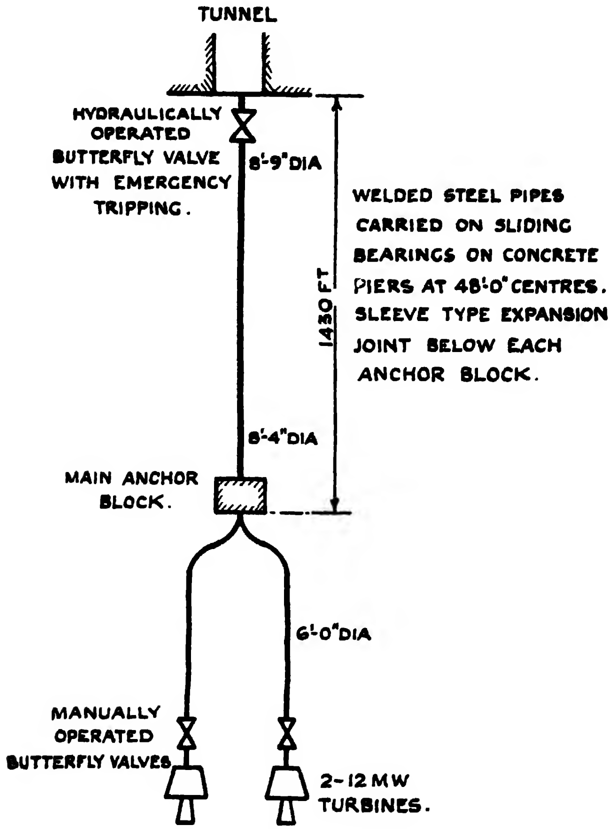

FIG. 584. Valve and Pipe Lines for 24 MW Station.

Balanced Disk Valve. This type is commonly called the butterfly valve and is used on both low and high-head pipe-lines. The valve consists of a smooth streamlined disk inside the pipe, and is pivoted at opposite edges so that it can be moved into a position at right-angles or parallel to the water flow corresponding to the closed and open positions, respectively. It is very compact and there is but little loss of head, and it can be built in the largest sizes required.

A by-pass valve is included for equalising the pressure on either side of the disc before opening the valve. An alternative is the simple cock body type which offers an unrestricted section to the water flow.

Surge Towers. Ignoring technical details, it may be said that a paramount function of the surge tower, or surge shaft, is to provide stability of operation. If no arrangements were made to deal with the situation arising when some or all of the turbines are suddenly shut down, *e.g.*, due to operation of the electrical protective gear or the overspeed devices, there would be a possibility of the pipe-lines, etc., being damaged, especially on high-head plants.

To take care of such operating conditions, it is usual to provide a surge tower which may be built of concrete to a height comparable with the operating head. It is connected to the pipe-line, and should the water to the turbines be shut off, the pressure is rapidly dissipated by the rise of the water in the tower. In some installations it is simply a vertical open concrete-lined shaft reaching to the surface of a hill and acts as a safety outlet when the pressure of water rushing down to the turbines becomes too great to be absorbed.

An incorrectly designed tower may give rise to highly destructive water-hammer effects. To be effective, a large diameter surge tower with a large diameter supply tunnel is necessary for low head plants. For high heads, the diameter of shaft required is much reduced for a given capacity as compared with low heads, but against this, other factors become decisive in requiring much greater heights and the provision of special storage chambers to limit the rise and fall of the surge swing.

Differences in head and the capacity and size of the supply tunnel, play a leading part in surge tower layouts.

Where the slope of a pipe-line, or part of it, on a medium or high head is gradual, a surge tower may be necessary at or near the turbines, or at the end of the flatter portion.

The connecting pipe will be the full diameter of the pipe-line protected, and will be enlarged at the top to act as a regulator while the velocity of the water is adjusting itself to new load conditions. This standpipe is carried above the forebay level, and serves as a subsidiary forebay nearer the turbines, storing or surplussing water when the flow is checked, and supplying it while the long column of water in the pipe-line is accelerating.

In this way the turbine speed is maintained more nearly constant, as the effective head varies but little. The larger the surface of water at the top of the surge tower, the less the variation will be.

Surge towers are sometimes referred to as surge tanks, surge pipes, and surge shafts, and consist essentially of a vertical open pipe or tank the lower end of which is connected to the pipe-line as near to the turbines as possible, and the upper end is above the surface-level of the supply reservoir.

Closing of the turbine gates is accompanied by a flow up the

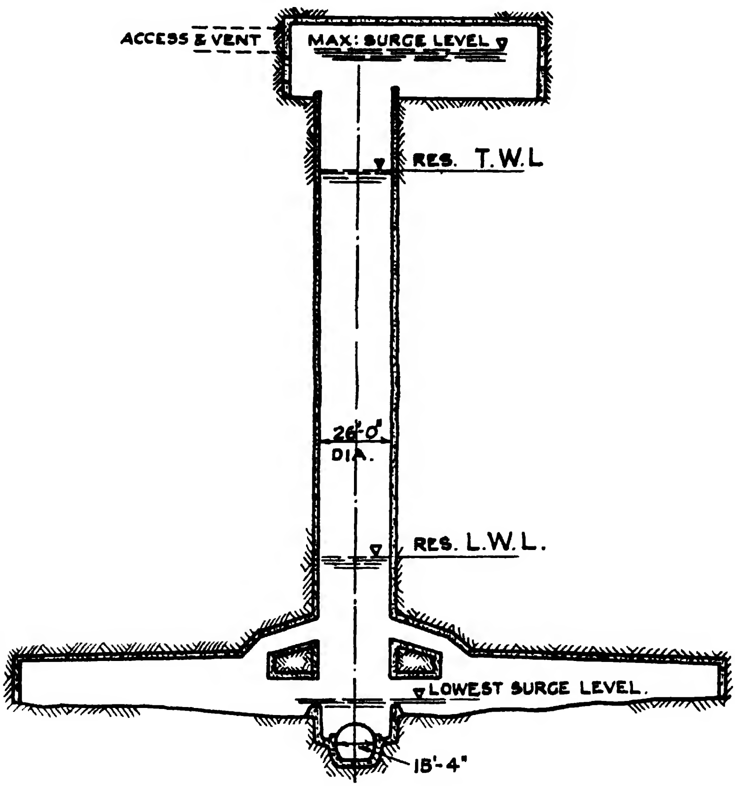

FIG. 585. Surge Shaft.

surge pipe. With a surge tower of adequate size, the consequent rise in pressure due to the retardation of the water column is much reduced. A tower is also useful with increasing load, as the drop in pressure at the turbines would be large owing to the necessity for accelerating the water column. Any sudden increase of load on the turbines is met by the flow down the surge pipe with a consequent reduction in the necessary acceleration in the pipe-line.

Should the head be so high as to render an open surge pipe impracticable, a closed pipe can be used.

Compressed air can be supplied to the upper part of the tank by a compressor of sufficient capacity, to replace leakage or absorption of air by the water.

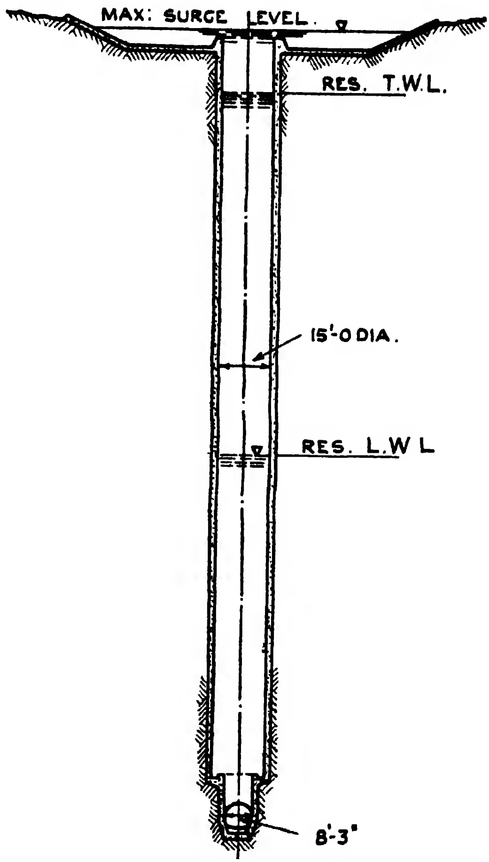

FIG. 586. Surge Shaft.

Careful attention should be given to the design of a closed pipe system, otherwise sympathetic surges may be initiated, which adversely affects turbine regulation. As an alternative, a differential surge tank may be installed, which consists of a vertical stand-pipe surrounded by a storage tank of larger dimensions, connected to it by inlets of restricted size. This type was considered for one

scheme, and whilst it enabled the diameter to be reduced from 100 to 80 ft., it would have meant increasing the height by some

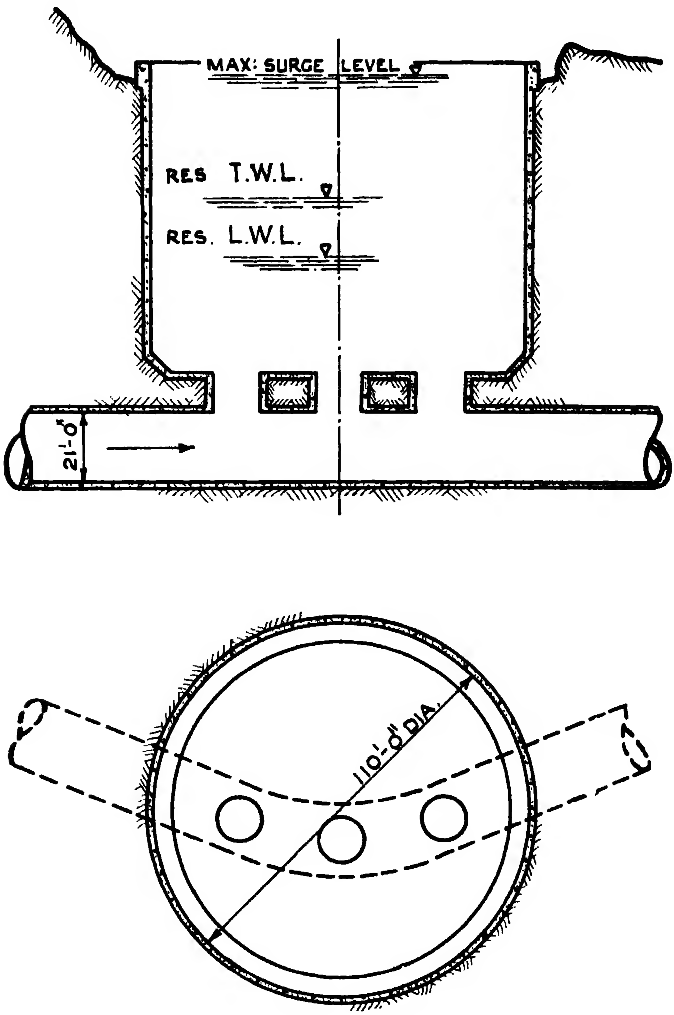

Fig. 587. Surge Shaft.

20 ft. and using an additional 1,000 tons of steel, so the idea was dropped.

When the pressure drop is excessive and unsatisfactory for speed regulation, a surge tank or tower is used; the principle

being to reduce the effective length of pipe and to supply or store water during a change of load while the flow of water in the pipe-line is accelerated or retarded. The surge tower may be necessary to protect the pipe-line from dangerous pressure rises should the pressure relief valve fail to operate and will also improve the speed regulation for small load changes.

Surge towers are generally built high enough so that the water cannot overflow even with a full-load change, but special overflow arrangements are sometimes included. An overflow pipe may also be fitted with a needle valve and disperser. Figs. 585 to 587 show different forms of surge tower construction.

Tail-race. The water leaving the draft tube has to be discharged into the river, and a tail-race is required for this purpose. The design should be such that the tube is water-sealed under all operating conditions, and that the free discharge of water is unimpeded.

Impulse turbines discharge their water directly into the tail-race without the assistance of a draft tube.

The race should be of adequate size to give a free exit to the water, and should have a deep water cushion to take the actual discharge, owing to the large residual velocity under high heads. Under very high heads a water cushion alone is insufficient to protect masonry or concrete, and protective measures are necessary. The tail-race should be of such a design that when the jet is deflected off the buckets it has unobstructed passage to the outside air by way of the tail-race passage.

The tail-race may be liable to become partly filled with flood water with a consequent reduction in net head. Exceptionally long races are prone to freezing in some climates, and should be avoided.

With a vertical draft tube the depth of water below the lower end of the tube should be at least equal to its outlet diameter. This may necessitate lowering the bottom of the suction pit.

The mean velocity in the suction pit usually varies between $1\frac{1}{2}$ to 2 ft. per second, and that in the tail-race from 2 to 4 ft. per second. The velocity in the tail-race should not exceed 2 to 3 ft. per second with heads less than 5 ft., as too high a velocity causes eddies and destroys the suction action by admitting air.

Provision can be made for stop logs to be inserted at the pit exit to enable cleaning and inspection to be carried out.

Where wide variations of water level obtain, it may be necessary to install a weir in order to maintain adequate level in the suction pit, and the slots for the stop logs can be used for this purpose.

Under such operating conditions it is advisable to adopt a vertical shaft machine in order that the head available can be effectively utilised.

Various arrangements of pits are possible; all machines can discharge into a common pit carried the entire length of the turbine house, or each machine can have a separate pit having its own exit at the side of the station. The first layout is cheaper, but should inspection, cleaning, or repairs to the pit be necessary, then the station will have to be shut down.

Where the power station is close to the river, the tail-race may be the river itself. If it is desired to shut down the station, or where a defector type of governing is used, the water jet must be diffused before being allowed to discharge into the tail-race. This can be accomplished by using diffusing discharge regulators or valves so arranged as to disperse the water in a hollow cone, when its energy is rapidly dissipated.

In some installations the water returns to the river by way of a short concrete tail-race in which gates are placed in the water-way, which enables the river to be shut out. A fish screen can also be fixed across the outlet.

Fish Passes. These are required by law in dams or power stations constructed upon natural waterways, and must be so arranged that fish can pass freely upstream to spawn.

The essential requirements of a fish pass are:—easy passage for fish, with uniform flow of water; a gradual ascent with no high barriers; minimum use of water; an approach or entrance into which fish are readily directed; be of durable and solid construction which will not be injured by freshets or readily disturbed when not in use. The entrance should be accessible so that the fish will be attracted towards it.

There are various types of fish passes, fish ladders, or fishways as they are sometimes referred to, some of which are:—(1) natural stream; (2) pool; (3) inclined plane; (4) hydraulic elevator; (5) tower.

(1) Where a small side stream of gradual slope is used, supplemented by a number of concrete barriers connecting the pond above the dam with the river below; or connecting the tail-race with a stream above the power station. Such a pass is easily surmounted, but requires a considerable quantity of water. Its entrance is usually some distance down-stream from the dam, and fish following the greatest flow are liable to miss it.

(2) Consists of a series of pools with a drop of about 1 ft. between successive pools, which may be constructed of concrete and arranged so that most of the flow is through orifices between pools. The water in the pools is comparatively still, and affords a resting place for ascending fish. The bottoms may be strewn with boulders to afford natural conditions. The velocity of the flow through the orifices is limited to about 8 ft. per second. With small narrow passes the discharge may be over the weir crest of each pool.

(3) These are arranged in a long slope having a gradient of about 1 in 10, with suitable arrangements to check the flow of water and afford resting places for the fish.

(4) The foregoing methods are effective for low dams but are not suitable for high dams associated with hydro-electric plants. For such dams it is desirable to reduce high velocities and turbulence, and create a hydraulic condition which will enable fish, irrespective of their size and condition, to ascend or descend the pass without difficulty. A hydraulic elevator type of fish pass has been developed by Glenfield & Kennedy to meet these conditions, and to combine improved amenity with economical construction (Fig. 588).

The principle of the pass is comparable to the transformation of a normal longitudinal section of a river from the horizontal to the vertical, without radical change in the hydraulic conditions. It is flexible in design to suit any specified height or type of dam structure, or almost any variations that may be required by a particular site. Fish of any size and in any condition can ascend or descend the pass with the minimum of effort, which is of special value should the dam be located in the upper reaches of a river. Here, summer or autumn, fish arrive in a weakened condition, usually being incapable of forcing their way against the velocity and hydraulic disturbance generally associated with the step pool pass. The absence of excessive turbulence, and the need to jump, makes the elevator type of pass suitable for the reception of spring fish, whilst the commodious freeway area of the inlet and outlet openings safeguard the fish from danger, and the enclosed structure gives privacy and protection against illegal interference.

The pass can be built into the dam in any position along its length, and the cost is considerably less than that necessary for an equivalent fish ladder. Should the dam be located in the lower reaches of a river where a large number of fish may be expected to arrive simultaneously, a more commodious pass similar in form to a

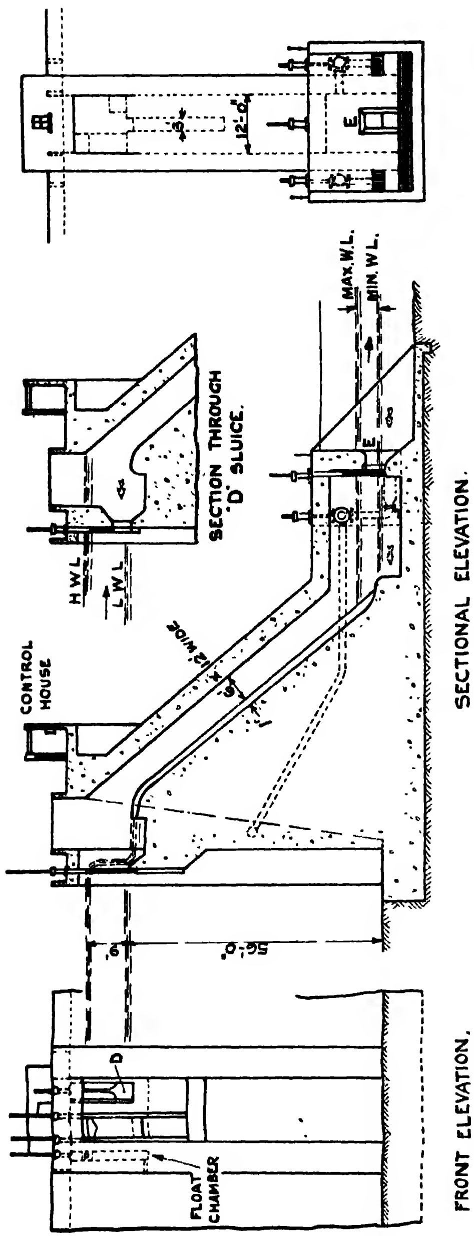

FIG. 588. Hydraulic Elevator Fish Pass.

ship lock could be adopted. Whatever form it may take, the principle of hydraulic elevation with a stream guide and controlled velocities and volumes remains the same.

From the point of view of power generation, the conservation of water is of primary importance, but if a fish run is to be maintained, it is important that a generous volume of water should be diverted through it, for the greater the volume the greater the inducement and confidence created. In a step pool pass the volume must necessarily be limited to prevent excessive velocities and turbulence, but with the elevator pass the volume can be considerable and yet retain a hydraulic condition which fish can easily penetrate.

These conflicting interests of power generation and fish movements can be allowed for by keeping the elevator pass open only during the season when the fish arrive. This arrival is usually limited to reasonably short and

known periods when surplus flood water is available, so that the maximum efficiency in both respects is obtained by this arrangement.

During the migratory periods, fish have a very strong urge to ascend or descend, and do not hesitate to enter the enclosed chambers if a good flow of water is provided, together with a flood of light at the exit. It is also important that the approach to the down-stream entrance should be located alongside the main stream, with a generous depth and a smooth flow. Excessive turbulence, particularly from turbine discharge, should be avoided, as fish apparently dislike this.

Competitive channels should be avoided wherever possible, and every care taken to ensure that the fish are diverted into the main approach channel without an alternative choice.

A similar pass is installed on the Liffey Scheme (Leixlip station) of the Eire Electricity Supply Board. The operation is entirely automatic, and push-button and manual control are also included. The cycle of automatic operations can be arranged to extend over any period of time, *e.g.*, one hour for fish escape, and three hours for fish entry, according to seasonal requirements. Perspex roof lights are included in the downstream end of the pass.

(5) Another design to enable fish to pass a dam consists of a concrete tower of circular cross-section standing in the reservoir. Inside the tower there is a series of chambers which rise spirally. Alternate chambers are provided with orifices which communicate directly with the reservoir. Sluices control the mouths of the orifices so that one, at a level appropriate to the depth of water in the reservoir, can be opened. The installation of fish passes requires careful study and planning, for various conditions will have to be allowed for according to the siting of the hydro-electric scheme.

In one American station, a new fish aid in the form of an electronic screen helps the fish to find their way down-stream past the headworks of the power plant. The device consists of a lattice of 10-ft. electrodes strung across the mouth of the intake canal with a ground wire buried at the bottom of the opening. From the control mechanism, electrical impulses at 700 volts are sent out at the rate of 6 per second. Fish entering the field of the screen are "tickled" by the impulse and diverted to the natural channel of the river.

In this country the difficulties presented as regards the ascent of the breeding fish and the subsequent descent of the fry and kelts, have to some extent been met by a fish pass with an adjustable

feed from the reservoir. A large proportion of the fry will pass through the turbines apparently without serious harm. If there is adequate clearance between the blades, and the speed does not exceed a certain value, small fish such as salmon smolts (5 to 6 in. in length) can pass through without harm. It is probably better to let the small fish avail themselves of a quick exit from the reservoir by this more readily found route, rather than compel them, by the interposition of closely interspaced gratings at the pipe-line intake, to seek it after probable delay through the fish pass intake.

Screened, but by a grating with relatively wide interspaces, the intake must be, however, to prevent the larger adults—spent and dropping down-stream as kelts—from getting involved in the turbines, with certainly fatal results to the fish.

A channel can be provided through which smolts can pass in a down-stream direction from the intake to a fish pass *viâ* a closed chute. This chute is hinged at its lower end, and attached to a float at the upper end which allows the mouth of the chute to remain submerged at a constant depth irrespective of the water level in the intake.

Sand Traps. Where the head on Pelton wheels is very high, the sand-blast action of solid matter in the water causes rapid wear of the nozzles, spears and buckets, and, in view of this, it is necessary to ensure a supply of water which is free from such matter. If there is a large dam and reservoir at the headworks, then no such difficulties are experienced.

In other cases, special sand traps arranged to be almost self-cleaning are included at some position in the path of flow. The velocity of flow is reduced to a low figure in order to allow the solids in suspension to settle out. The flume is both widened and deepened so as to reduce the velocity of flow to one-half feet per second or less.

In one case, records showed that with silty water, Francis runners and Pelton wheels of medium head only had a life of 300 service hours. The excessive silt was removed by settling tanks, and the life was increased by ten times.

Jet Dispersers. The release of water through sluices or valves at the bottom of high dams may create difficulties due to the large amount of energy possessed by the discharging water. Unless the energy can be dissipated within reasonable limits by some means it will cause scouring of the channel below the dam and possibly result in ultimate damage to the dam foundations. One way of partially overcoming this problem is to discharge the water into a cushion

pool (Fig. 589), but this is not an entirely satisfactory solution because the swirling currents still remain, and to prevent damage the pool must be very large.

The jet disperser (Fig. 590) is the most effective means of dealing with the discharge water. The disperser is attached to the end of the outlet pipe and breaks up the jet into a conical shower of drops, so that their energy is absorbed by the air. It can be tilted slightly upwards and inclined away from the river bank so that the dis-

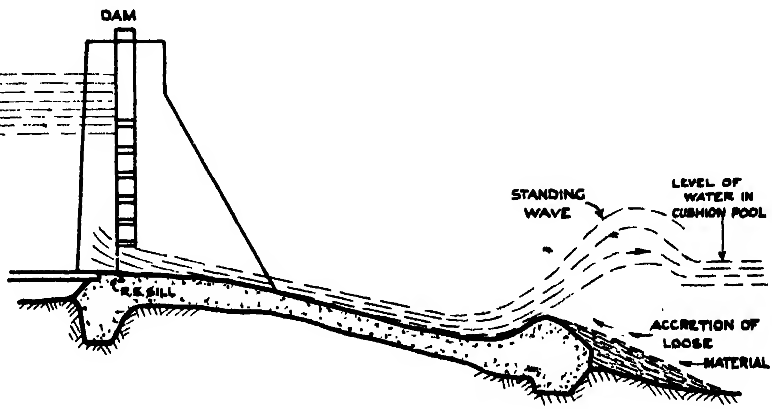

FIG. 589. Flood Gate—Sill and Terminal Bucket.

charge is kept clear of the building and falls chiefly on the water cushion provided by the tail-race.

Stop Logs. Suitable lifting gear is provided to enable these logs or racks to be inserted and withdrawn from the guides. Provision should also be made for storing them. In some installations intake gates are omitted, stop logs being used to isolate the turbine. This effects a saving in cost, but in the event of a governor failure, the results may prove very serious.

Buildings. As the power plant buildings, apart from dams, are perhaps the most conspicuous part of a hydro-electric scheme, it is desirable that they should be of satisfactory appearance. harmonising as far as practicable with the surrounding countryside. A simple and dignified design usually gives the best effect and can often be obtained at reasonable cost. Concrete, stone and brick of various types have all been used for the superstructure. To prevent flooding, the buildings should be placed above flood level and a minimum of combustible material should be used to reduce fire risk.

The principal building, namely, the turbine house, may be

steel-framed, with walls composed of pre-cast concrete blocks, or, alternatively, brickfilling finished in rough cast on the exterior. Some are roofed with Siegwart pre-cast concrete units and faced with pre-cast slabs specially finished to harmonise with local surroundings. Local slates have been used for the roofs, and the buildings designed with a view to preserving the amenities of the immediate surroundings. Flat concrete roofs having an asphalt

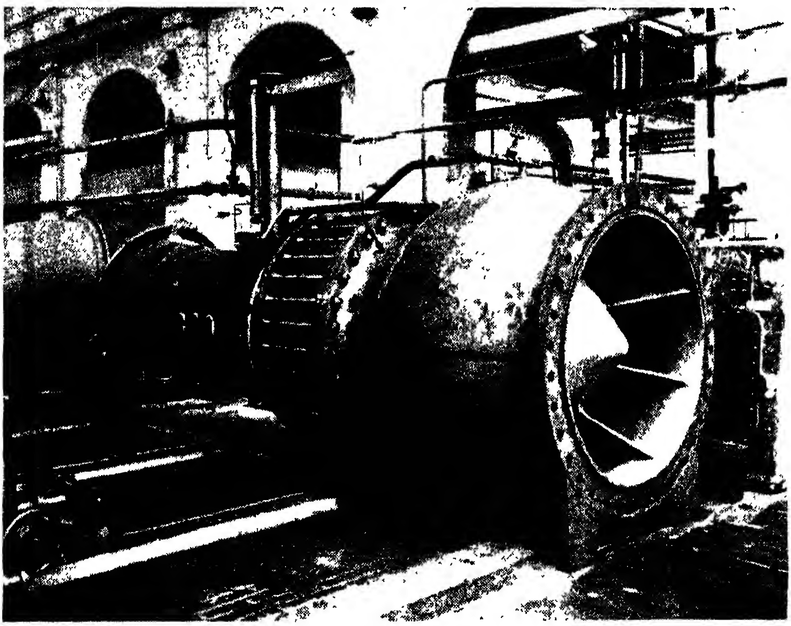

FIG. 590. Cylindrical Balanced Streamline Disperser Valve (English Electric Co. Ltd.)

finish are most commonly used, but local conditions may suggest other forms of construction.

To blend the walls with the concrete dam, a sand cement brick is suitable for the exterior facing.

Concrete with or without reinforcement is usual for the foundations and sub-structure.

The building frame for larger stations is generally of structural steelwork, the columns being spaced according to the machines, and they carry the crane runway girders and, in some designs, the roof beams.

The walls—concrete, stone, or brick—of small stations are frequently used to support the roof, the crane girders being carried on pilasters which form part of the walls. The finish of the interior walls should be such that a clean and pleasing effect is obtained, *e.g.*, glazed bricks and painted walls, preferably of light coloured tint, afford improved lighting.

The wall windows are an important detail, and careful proportioning is essential if a satisfactory appearance is to result. Window sashes may be of metal, and the glazing preferably of the wire-wove type, with a number arranged for controlled opening. Instead of the conventional steel window sash, glass brick may be used in all of the openings in the exterior walls, not only because of its superior appearance, but also to keep the heating of the buildings as small as practicable.

The main crane spans the width of the turbine house, and travels its entire length. The capacity of the crane depends on the size of the machines, and provision should be made for installing and dismantling the plant. The crane should be arranged so that it is possible to lift machinery off the transport wagon for erection, and lift parts off the machines for dismantling. A loading bay should be provided in the turbine house to admit rail wagons or road vehicles. A workshop at one end and loading bay at the other gives the crane access to all parts of the plant. An alternative arrangement is to have a workshop adjoining the loading bay.

The main floors are of concrete with granolithic or tile finish to harmonise with wall finish. Other floors are usually of reinforced concrete with smooth finish designed to suit the plant to be carried thereon.

Care should be taken in the selection of materials used for the construction of the various sections of the works, for accidents may result in the loss of life. Very heavy dead weights have to be supported, and, in addition, heavy thrusts and tilting effects due to water pressure have to be provided for.

It is often desirable to house the head or control gates, and the building required depends on the number, size and type of gates used, together with the hoists or controls installed.

The ventilating system for the buildings can be augmented by the alternator air-cooling system in such a way that during the winter season part of the air heated by the machines is bled off to warm the buildings. Secondary heat exchangers may be used as an alternative to bleeding the closed air system, and in this method

the heat in the alternator cooling air is given up to an entirely separate stream of air which is used for station heating. It is very costly, and may amount to some four times that of air bleeding.

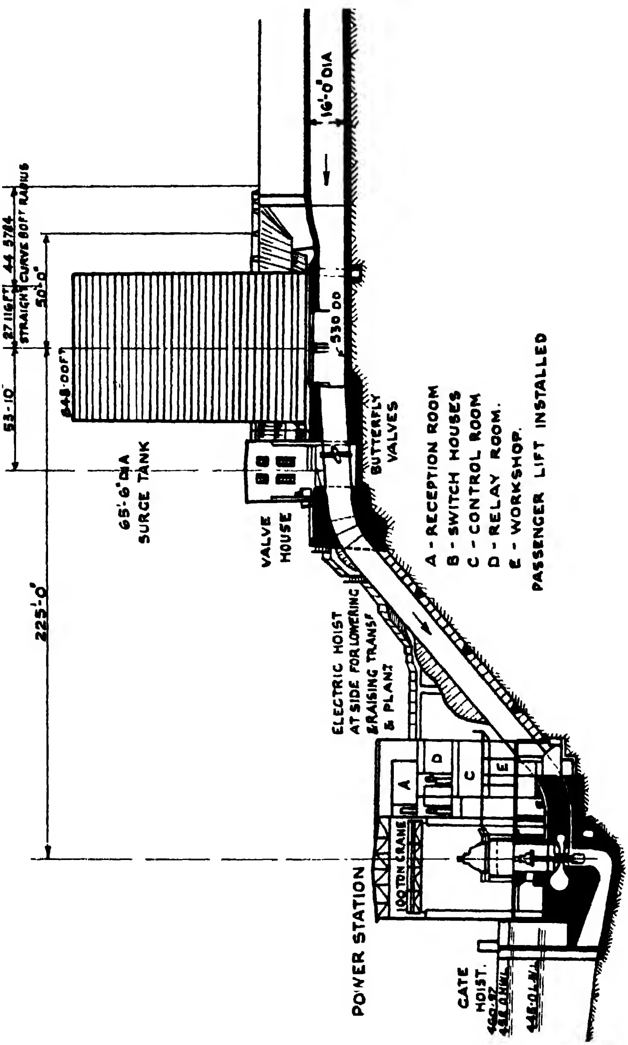

FIG. 591. Layout of 30 MW Station. (2–15 MW Kaplan Turbines.)

Heating the buildings with warm air from the machines is satisfactory under reasonable load conditions, but during times of light load, when heating is usually required, the air leaving the machines is not very warm, and if discharged into the buildings it only creates

a draught. A hot-water heating system is useful during shut-down periods and exceptionally cold weather.

The switch houses usually adjoin the turbine house, and may be placed parallel or at right angles to it.

Workshops, offices, stores, battery rooms and control room all have to be provided for, and site conditions quite often dictate the layouts possible.

Table 97 gives details relating to three stations, and Fig. 591 shows typical building accommodation requirements.

Fig. 592 shows interior of turbine house with vertical machines at alternator floor level.

TABLE 97. *Comparative Building Data*

Station, and Head (ft.)	A-2 (100)	B-2 (380)	C-2 (190)
Plant	3 11 MW vertical Francis; 1 250 kW. House Set.	2 12 MW vertical Francis; 2 500 kW. House Sets.	2 5 MW vertical Francis.
Turbine House cu. ft.	399,200	145,800	165,000
cu. ft./kW.	12·0	6·0	16·5
Switch House, Control Room, Offices cu. ft.	151,000	150,000	116,000
Auxiliary Plant and Cable Chambers cu. ft./kW.	4·6	6·3*	11·6
Workshop and Living Quarters cu. ft.	54,000	12,200†	24,000
cu. ft./kW.	1·64	0·51	2·4
Totals cu. ft.	604,200	380,000	305,000
cu. ft./kW.	18·24	12·81	30·5

* Control room provides for remote control of three other stations.
† Workshop only.

The sizes of machines and turbine houses bear no direct relation to the capacity of the installation. For a given capacity of, say, 10 MW, a low head station (50 ft.) requires a large quantity of water and large and slow-running machines. At a medium head (400 ft.) the quantity of water would be about one-eighth of that for a low-head plant, the machines would have a higher speed, be much smaller, and occupy less building space. In a multiple-unit station, with vertical shaft sets, the turbine house building is tall because of

the vertical setting and the necessity to allow dismantling for overhaul, which involves placing the crane high enough to permit large

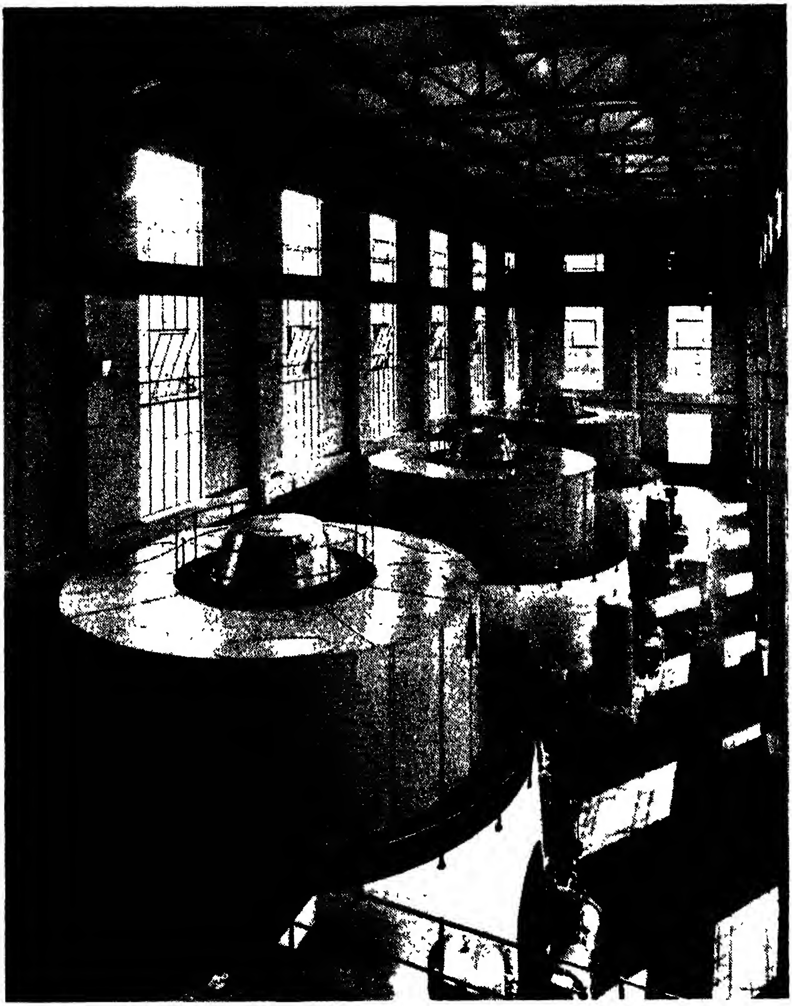

FIG. 592. Tongland Turbine House with 3–11 MW Sets Operating at 114 ft. Head and 214 r.p.m. (English Electric Co. Ltd.)

heavy parts to be carried to the repair shop or loading bay over the top of other machines.

The lowest and most compact stations in relation to capacity

are those having a single horizontal-shaft Pelton wheel, where dismantling does not involve carrying large pieces of plant over the top of the machine.

A Kaplan turbine runs at a higher specific speed than a Francis turbine, which tends to reduce the size of the runner and alternator, but necessitates a low setting of the runner to obviate cavitation and deep foundations to accommodate the draft tube.

MECHANICAL PLANT

Turbines. There are three principal types of water turbines, namely: (1) Impulse; (2) Reaction; (3) Propeller.

Turbines are made in all sizes up to 120,000 H.P. in a single machine, and operating speeds vary from less than 100 r.p.m. in the larger machines to upwards of 1,000 r.p.m. for small output machines.

If the whole of the available power can be utilised according to the head, then:

(1) Output for a given turbine varies directly as the square root of the cube of head.

(2) Normal speed with fixed blades varies directly as the square root of the head.

(3) Quantity of water used varies as the square root of the head.

Choice of Turbine. This depends on a number of factors, which include the output, working head, nature of load and the speed. There should be as few machines as loading conditions will permit, for the larger the output of individual machines, the lower will be the cost per kW. of the plant installed, and, generally speaking, a higher efficiency will result.

For very low heads, the propeller type can be used, and if the head and load variations are considerable a Kaplan turbine gives an improved range as compared with the fixed-blade propeller type.

The reaction type is not suitable for very high heads, as the high velocity of the water causes rapid wear, which results in large leakages through the clearance spaces. Friction losses are also high. The impulse or Pelton wheel turbine is used for very high heads, and the speed is lower than for a reaction turbine. They are simple and robust, easy to control, and the maintenance charges are reasonably low. An impulse turbine may be preferred to a reaction machine for medium heads, even at the expense of efficiency.

In one case, a comparison between vertical-shaft Francis turbines

and vertical-shaft Peltons with four jets on a single wheel, showed no advantage for Peltons, which would occupy more space, and Francis turbines were adopted. Vertical machines offer many advantages over horizontal ones especially if there are great variations in tail-race level. Horizontal machines necessitate keeping the turbine house floor above the highest tail-race level, or, alternatively, making the lower part of this house watertight. The grouping of two or more runners cannot be done on vertical machines.

Factors influencing the choice between horizontal and vertical machines are :—relative cost of plant, foundations and building space, and the layout of plant generally. In the vertical machine, the weight of the rotating parts acts in the same direction as the axial hydraulic thrust. This requires a thrust bearing capable of carrying a relatively heavy load and of working at the maximum runaway speed. There is no great difference of efficiency between the two types but the horizontal shaft turbine is more accessible. With the horizontal type there may be two turbines driving one alternator and the turbines would operate at a higher speed bringing about a smaller and lighter alternator. The horizontal machine would occupy a greater length in the station than the vertical machine but the foundations need not be so deep and the question then becomes one of cost, not only of machines, but also the station in general.

Impulse Type. The Pelton wheel is fundamentally suitable for dealing with high water velocity rather than large quantities of water at low velocity which must, of necessity, be used to produce the same power under different conditions. The head between the tail-race and nozzle is ineffective in producing power.

Two or more jets may be used on a single wheel, or two wheels may be coupled together on the same shaft each with one or two jets, and so obtain a higher speed for a given head (Fig. 593).

The majority of impulse turbines are of the horizontal shaft type, and in some designs two wheels are mounted at the ends of a common shaft with the alternator in between. The horizontal machine is simpler than the vertical type from constructional and maintenance points of view. The wheel passages are not completely filled, and the water acting on the wheel vanes or buckets is under atmospheric pressure. The water may be supplied at one or more points at the periphery of the wheel, and the energy so applied is entirely kinetic. Two jets operating at an angle to each other is usual, but increasing the number of jets on a horizontal machine causes interference between them.

The pressure energy of the water is transformed entirely into kinetic energy in the nozzles, and the flow through the rotating parts is under atmospheric pressure. The absolute velocity of the water leaving the rotating parts is reduced as nearly to zero as possible, so that all the kinetic energy of the water is given up.

Impulse machines may be arranged as follows :—

(1) Horizontal shafts (single or double overhung) or vertical shafts.

(2) Single or multiple nozzles.

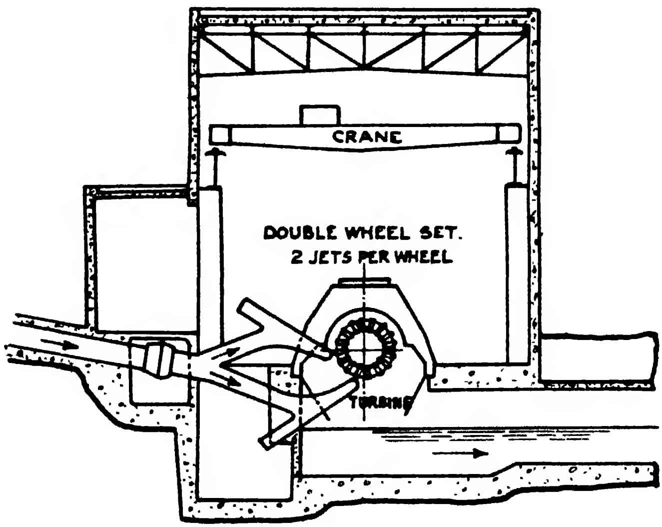

FIG. 593. 30 MW, 1,362 ft. Head, Pelton Wheel.

Six nozzle vertical impulse turbines are in operation and these permit of higher specific speeds while maintaining the high values of efficiency for a single jet. These are 62,000 H.P. sets running at 300 r.p.m. under a head of 1,120 ft. at a specific speed of 11·6.

Due to the smaller discharge as well as the higher velocities allowed, the tail-race passage is much smaller than that of the reaction turbine.

The loads of the turbo-alternator are concentrated at the two bearing points for either double or single overhung machines.

The peripheral speed of an impulse turbine is a little less than half the theoretical velocity of the water, and in low-head turbines the speed can be varied within wide limits according to the design.

taken into account are :—the alternating stresses due to impact of jet ; centrifugal forces at normal and runaway speeds ; and stresses set up by application of the full jet with the wheel at rest, *e.g.*, under short circuit conditions. A 15,000 H.P. wheel operating under a head of 1,650 ft., and running at 375 r.p.m. ; each bucket sustains a thrust from the jet approaching 28 tons, 6·25 times per second or 540,000 times per day. The buckets are the most vital part, and should be designed and constructed to resist both the centrifugal force and the repeated impact of the jet without the possibility of backlash developing. With one bolt for fixing, the load sharing difficulties experienced with two bolts is eliminated ; the bolt takes care of the shear stresses, and the key the compressive stresses. The buckets and discs are of cast steel, and the buckets are interchangeable. In the English-Electric design, the back of every alternate bucket bears against a proportion on the circumference of the disc, machined out of the solid metal (Fig. 595).

Some buckets are pressed out of stainless steel, the splitters being welded on after forming.

Nozzle design is important, and a circular form with a concentric regulating needle of " pear " shape provides a smooth solid stream of water. This regulating needle is controlled by an automatic governor which actuates a deflector, and cuts into the jet so diverting the water from the buckets. It is such that it is responsive to load changes, and a dashpot arrangement prevents undue hunting. Braking is by means of a counter jet.

Reaction Type. The reaction turbine is designed to cater economically for heads beyond those on which the propeller or Kaplan turbine operates, and below those on which the impulse or. Pelton wheel can most economically operate (Figs. 596 and 597).

There are broadly four groups of reaction turbines :—

(1) Radial inward flow.

(2) Radial outward flow.

(3) Mixed flow ; radial and axial.

(4) Axial flow ; propeller types.

The water flows through a spiral casing inwards through the runner, and acts on a series of blades running between the hub and the outer runner ring. Use is therefore made of the kinetic and potential energy of the water. The casing accommodates a ring of movable guide vanes throughout the circumference of the runner. Mechanical linkages are mounted on a regulating ring which is operated by Servo mechanisms from the governor to open and close

gates, and so regulate the flow of water to the runner, after which it passes to the draft tube. The links which couple the guide vanes to the regulating ring are made breakable, usually by a transverse saw cut across their middles. Should any debris lodge between the guide vanes, the associated links will break and prevent the regulating ring from locking. Replacement of a link is a simple operation. The depth of saw-cut is determined experimentally so that the correct breaking load is obtained.

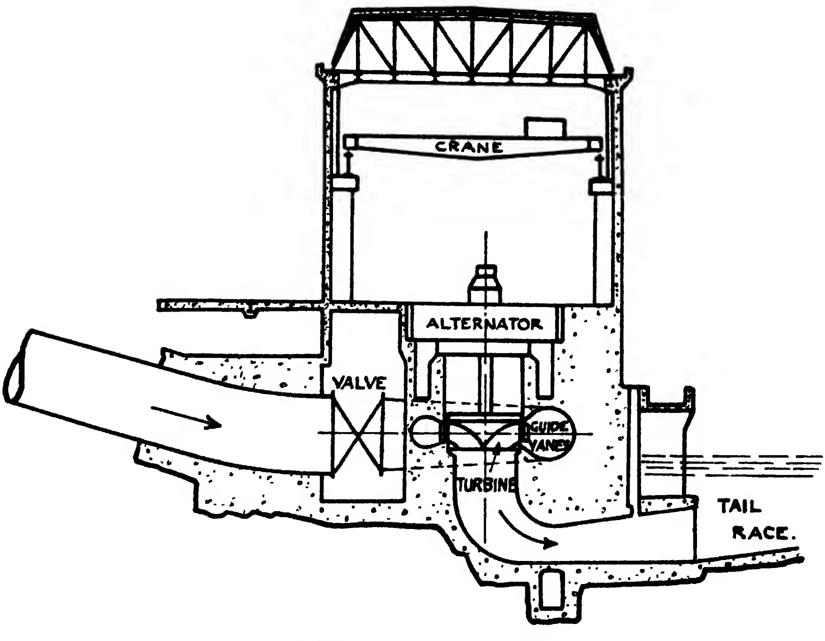

Fig. 596. 19 MW, 175 ft. Head Francis Turbine.

In the Francis turbine, the water passes through the machine firstly in a radial direction, and afterwards in an axial direction. Such machines are of large water capacity, and are frequently of the vertical type. The water is controlled by movable inlet guide vanes through which the water passes in its way from the spiral casing to the runner. The runner itself consists of some fifteen or more blades joined together at the top and bottom, and may be cast in one piece of bronze or steel, or built up by welding.

Correct design of the draft tube is essential if water hammer and erosion are to be eliminated. It is found that incorrect design

produces a suction effect on the lagging edges of the runner blades, and chemical and mechanical action on the edges results in pitting. Stainless steel may be welded on to the runner blades to prolong their life.

Braking of runners is effected by welding small vanes on to the

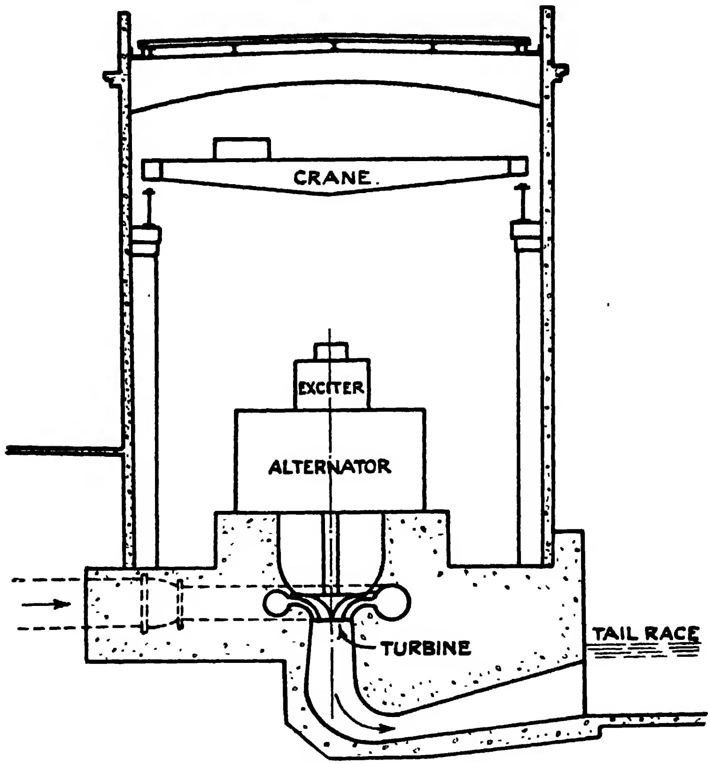

Fig. 597. 32·5 MW, 910 ft. Head Francis Turbine.

back of the steel ring containing the main runner and directing against these vanes a jet of water from a special nozzle.

Large reaction turbines are usually of the vertical type to effect economy in building space, the alternator being mounted above the turbine, thereby being free from flooding.

The runner passages are completely filled with water which acts on the runner blades, and is under a pressure above atmospheric. The water enters all round the periphery of the runner, and energy in the form of both potential (pressure) and kinetic, is utilised by

the runner. The pressure energy of the water is only partly transformed into kinetic energy in the stationary parts of the turbine, *i.e.*, the guide vanes, and the flow through the rotating parts takes place under varying pressure, the passages remaining full. The forces on the rotating parts are due both to change in pressure and in the direction and velocity of flow of the water. Both the pressure and the absolute velocity of the water are reduced as the water gives up its energy to the runner.

The principal features of the reaction turbine are :—runner ; guide vanes or gates ; speed ring pit liner (vertical machine) ; casing or approach flume ; and the draft tube.

The draft tube connects the exit from the runner with the water level in the tail-race, and enables the machine to be placed some distance above the race without loss of head between the runner and race.

The upper limit in respect to head under which the reaction turbine may be employed is in general due to the following :—high velocity of water to and in the runner which would cause rapid wear ; high frictional losses with large runner surfaces turning in water ; leakage past clearance spaces becoming unduly large, and very high pressures present difficulties in the design and construction of casings. The tendency is to gradually extend the upper limit of head at which these turbines operate. The controlling factors in some installations are that of improved efficiency, and a reduced cost of power station and pipe-lines as compared with Pelton wheels.

Reaction machines may be arranged as follows :—

(1) Vertical or horizontal shafts.

(2) Single or multiple runners.

(3) Open runner-pit, concrete spiral flume, or metal scroll-flume settings.

The efficiency of a vertical shaft turbine may be some 1 to 2 per cent. higher than for a similar horizontal machine, especially for high specific speeds. This is due to the absence of a suction bend near the runner.

Pitting on the backs of the runner blades near the outlet edges is sometimes experienced. A turbine operating for prolonged periods at partial gate opening is likely to suffer from pronounced cavitation. Stainless steel inlays on surfaces of the runners subject to cavitation have proved satisfactory, and led to the adoption of cast stainless steel runners. This reduces maintenance costs due

to cavitation, corrosion and erosion sometimes met with on bronze runners. Cavitation occurs if the pressure in the runner falls below the vapour pressure of the water owing to vortices or unduly high suction head, and results in the accumulation of vapour on the back of the blades. The "condensation cracking" of these vapour cavities when they collapse causes violent water-hammer, which results in pitting of the blades. The greatest permissible suction head, $hs = A - C.H.$ Where A—Atmospheric pressure ; H—Total head ; C—Cavitation constant.

Francis turbines . .	C ———— 0·04–0·45
Kaplan turbines . .	C ———— 0·5–1·9

In one installation with 15 MW, 515 ft. head, machines, the effect of cavitation on the runner was minimised by reducing the suction head as far as practicable, the maximum being 12 ft. measured from the centre of the inlet.

The inlet and outlet edges of the blades are streamlined to avoid impact and eddying, and water passages are ground to a smooth finish to ensure high efficiency.

Reaction turbines are comparatively cheap, and particularly suited to low fall installations. They are only affected by backwater to the extent that the tail-race level is increased, and can be placed between the headwater and tail-race levels with a draft tube, providing there is sufficient water above the turbine to prevent air being drawn into it. Part of the effective head is then obtained from the suction on the tube, but this should not exceed 25 ft. The control of the water flow to the runner is effected by means of gates, of which there are numerous designs. Horizontal and vertical turbines are employed according to the site conditions, and, in the case of low and medium falls, two or more runners may be arranged on a common shaft to obtain a higher speed and a consequent reduction in the cost of alternators.

Vertical turbines require smaller foundations, and fewer machines are required for a given output.

In one station, horizontal Francis turbines have double-runners with cast-iron spiral casings and a single discharge. The turbines are each 22,000 H.P., and operate with a head of 160 ft., running at 300 r.p.m. The runners are of cast chromium stainless steel, this material being chosen to resist cavitation. It was considered better than either gun-metal or cast steel, and enabled the centre line of the shaft to be placed 14 ft. higher above the tail-race water

level than would have been possible with these materials. The guide vanes are of cast steel, and the links are designed to break as soon as the load exceeds a predetermined figure. Arrangements are provided to prevent jamming.

Changing of the runners has also to be resorted to in an endeavour to eliminate severe pitting and erosion by cavitation. Changes in operating head may occur on some plants due to large storage capacity and hydrological conditions in general. In one plant a gross hydraulic head of 170 ft. was chosen as the point for changing to high-head runner, and 150 ft. to low-head runner, the area in between being regarded as neutral. Runner buckets are somewhat difficult to cast as a whole and they can be cast individually at lower overall cost and then welded to the crown and band.

Propeller Type. A particular form is the Kaplan (Fig. 598) in which the blades have an adjustable pitch to deal with a wide range of operating heads, and it is suitable for large sizes and very low heads.

The propeller turbine is one wherein the flow within the wheel itself is in a direction mainly parallel to or cylindrical about the axis of rotation. The fixed blade runner is more robust than the Kaplan, and moreover, in some cases, has a higher maximum efficiency. If then, the lower efficiency of the fixed blade type at part loads is not a detriment, its mechanical advantages and high maximum efficiency may prompt its choice.

The Kaplan is more complicated and more expensive than other types, but it has a higher efficiency over a longer range and wider variations of head and load, and has a higher specific speed which results in a saving in the cost of the alternator. This higher efficiency is achieved by making the runner blades movable so that at any given load the opening offered is proportional to the quantity of water passed. The operation of the movable blades is automatically controlled, and is made by an oil-pressure Servo motor which can be housed either in the hub of the runner or at some other convenient position such as the coupling between the turbine and the alternator. Whatever position is chosen, it is necessary to have a hollow shaft for the turbine and alternator to accommodate the operating mechanism. The forces required to turn the blades are balanced; therefore the shaft and couplings do not have to carry any additional loads when the runner blade settings are being adjusted. As the whole of the hub is full of oil ánd the oil pressure is considerably higher than the water pressure in the runner chamber,

there is no possibility of water entering the hub. The escape of oil past the runner blades is prevented by rubber sealing rings.

Owing to the level at which a Kaplan runner has to be mounted relative to the tail water level, practically all turbines are of the single runner vertical shaft type.

Early machines were limited to relatively low heads, but they are now used for heads approximating 200 ft. With higher heads, cavitation troubles are experienced.

The production of large and awkward castings for the runner blades presents problems. The lower end of the runner has a

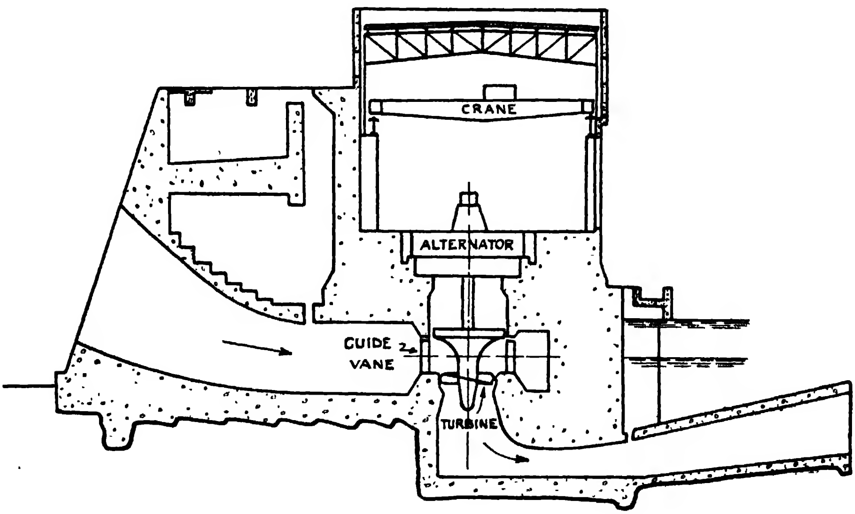

FIG. 598. 7·5 MW, 50 ft. Head Kaplan Turbine.

streamlined conical "nose-piece" to ensure that there is but little turbulence when the water leaves the runner blades. Since the performance and efficiency of the turbine depends primarily on the profile and finish of the blades, these parts are ground accurately to template on both upper and lower faces, and finally given a high surface finish. The blade profiles are based on extensive laboratory test results, as well as actual performance data.

The favourable efficiency curve makes it possible to use a few large units instead of many small ones, thereby effecting a saving in initial cost.

Propeller blade erosion can be reduced by welding on new tips slightly inclined to the normal plane of the blades. The idea is to

make the lower side of the blade tip keep intimate contact with the water.

Propeller wheels of large diameter and capacity are used for low variable heads. The angle that the blades can be turned through in a given time becomes smaller as the runner diameter increases, and speed changes may be partly due to the slow adjustment of the blades to meet the new conditions. A higher flywheel effect may be required for large Kaplans than for comparable Francis machines.

With propeller wheels, both the specific and actual speeds are higher, and direct driving is possible with very high efficiency.

With a movable-blade Kaplan it is possible to keep the speed uniform over extreme variations of head. The speed of the Kaplan is higher than that of a Francis turbine, thereby allowing the diameter of the alternator to be reduced. The reduction in the length and width of the building on this account compensates for the deeper excavations necessitated by using the Kaplan turbine. There are Kaplans of 42 MW, 10 kV., 136 r.p.m., operating at 100 ft. head.

Loss of Output. High water velocities, incorrect passage through wheel, discharge or draft tube, cause drop of output. Loss may also be attributable to high tail-race water, air leak into draft tube or obstruction in runner, and also erosion of blades.

A check is sometimes desirable if the water available is limited, and additional capital expenditure is necessitated for impounding. Venturi "throats" can be inserted and a check taken. A Pitot tube, suitably rated, can be used on existing plants.

Overload Capacity. It is desirable that the overload capacity available during the winter should be known, assuming full-gate opening, maximum head conditions, and an alternator maximum temperature rise within the specified limits. Turbines may do $12\frac{1}{2}$ per cent. overload with a reduction in the factor of safety, and the alternators would have a similar overload capacity. The exciter is the limiting feature, but this can be met if steam stations deal with most of the wattless current, thus allowing the power factor of the hydro-stations to be raised.

Type of Turbine Setting. There are two principal types of setting, namely :— (1) Open flume ; (2) Cased turbines : (*a*) Cylindrical and (*b*) Spiral.

The open flume or runner pit is chiefly used for low heads with concentrated falls or perhaps with a short canal. An open pen-

stock setting is one where the entry to the runner has no casing, but is placed in an open forebay, at any convenient depth below the water surface such that eddies and suction of air through vortices will not take place. The turbine is completely submerged, which results in a simple and comparatively cheap plant. A disadvantage is that the pit must be drained to enable inspection and maintenance to be carried out on the turbine and guide vane mechanism. The turbine should have an adequate head of water above it, otherwise a sudden increase of load may draw down the water to a dangerous

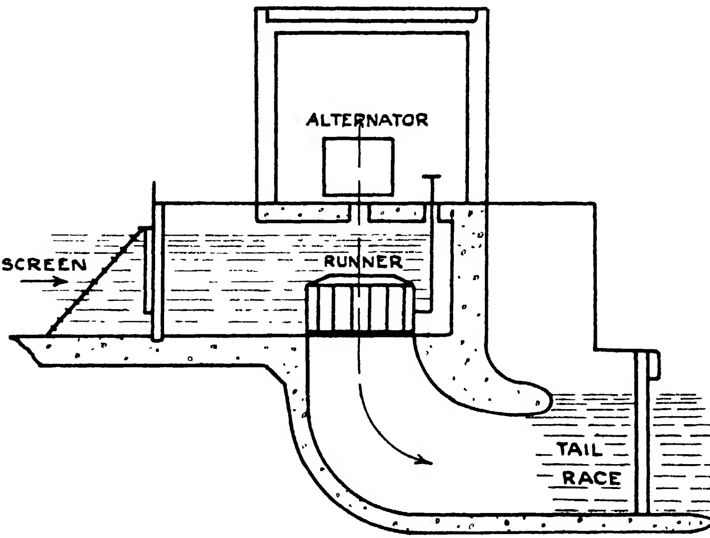

FIG. 599. Low Head Layout.

level and allow air to enter. Such a condition would break the draft tube vacuum and stop the turbine.

The gross sectional area just upstream from the racks should be sufficient to give a velocity of flow of about $0{\cdot}03\sqrt{2g \,.\, h}$; at the gates $0{\cdot}07\sqrt{2g \,.\, h}$, and approximately the same in the flume.

To afford adequate waterway with suitable gates, one or more piers with rounded corners or cutwaters upstream should be provided. It may be necessary to design the flume walls for water load on one side only. The wall and floor of the pit carry fairly heavy loadings, and adequate reinforcement should be used. Attention should be given to all joints for water-tightness, and water stops should be provided and placed to protect reinforcement. If possible

the flume should be constructed as a monolithic structure, at least up to the maximum water level. The flume roof is usually the alternator room, and is designed to carry the runner, the thrust on the runner, the alternator in addition to the uniform live load such as would result by placing the heaviest piece of plant anywhere on the floor.

The spiral casing is the more usual form, the shape being such that the water velocity varies throughout according to the rules of

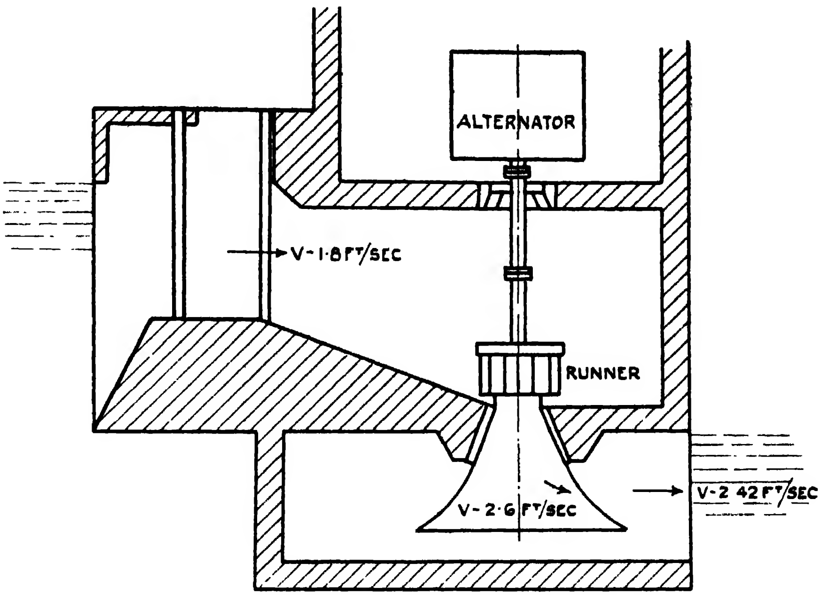

FIG. 600. Open Wheel Setting.

free vortex flow, *i.e.*, the velocity is inversely proportional to the radius. It is of a logarithmic spiral form which reduces friction loss, ensures a smooth flow, and gives almost complete freedom from erosion. The casing is so designed that the water is gradually and constantly accelerated up to the point where it meets the runner. The spiral casing may be cast in one or more pieces or built up by welding together steel plates.

There are various forms of scroll construction :—concrete ; steel-plate ; cast steel.

As the concrete approach flume often fixes the machine spacing, it should be kept as small in width as correct design will

permit. Concrete flume design usually allows for a velocity of flow $= 0{\cdot}06/0{\cdot}08\sqrt{2\ g\ .\ h}$. The horizontal arrangement of spiral around the wheel should be such that no additional distance between machines will be necessitated beyond that required at entrance.

Theoretically, a circular form of the scroll case would be the most effective hydraulically, but with large machines this would require such a wide water passage as to necessitate extra spacing between machines. The height of scrollway is therefore generally in excess of the width. With a low head the elevation of the roof

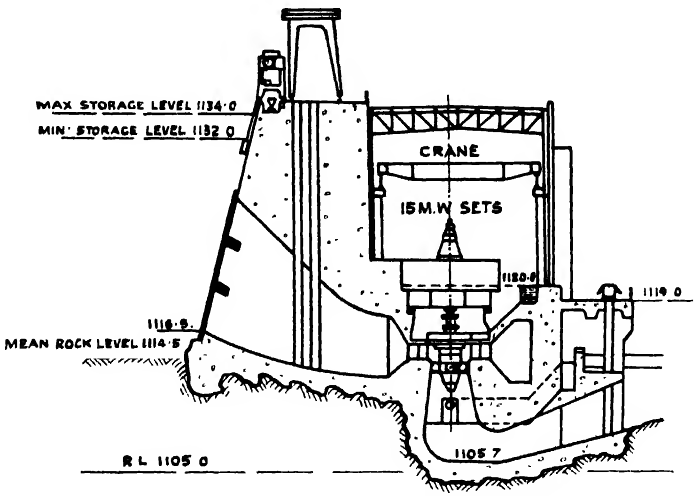

FIG. 601. Reinforced Concrete Scroll.

of the scroll may be fixed by the necessary depth below head water level for a suitable water seal. This may necessitate a greater depth of spiral flume below the wheel centre line than above, in order to maintain the correct velocities in the flume. On the other hand, where sufficient head is available for a water seal, the greater part of the scrollway cross section may be placed above the water wheel centre line, thereby reducing excavation.

Concrete scrolls are limited to low head installations up to about 65 ft. The complicated formwork and reinforcement required for a concrete flume make it expensive, so that other methods of construction have to be used. The casings are moulded in concrete.

Steel-plate scrolls are used for heads as low as 40 ft., with an

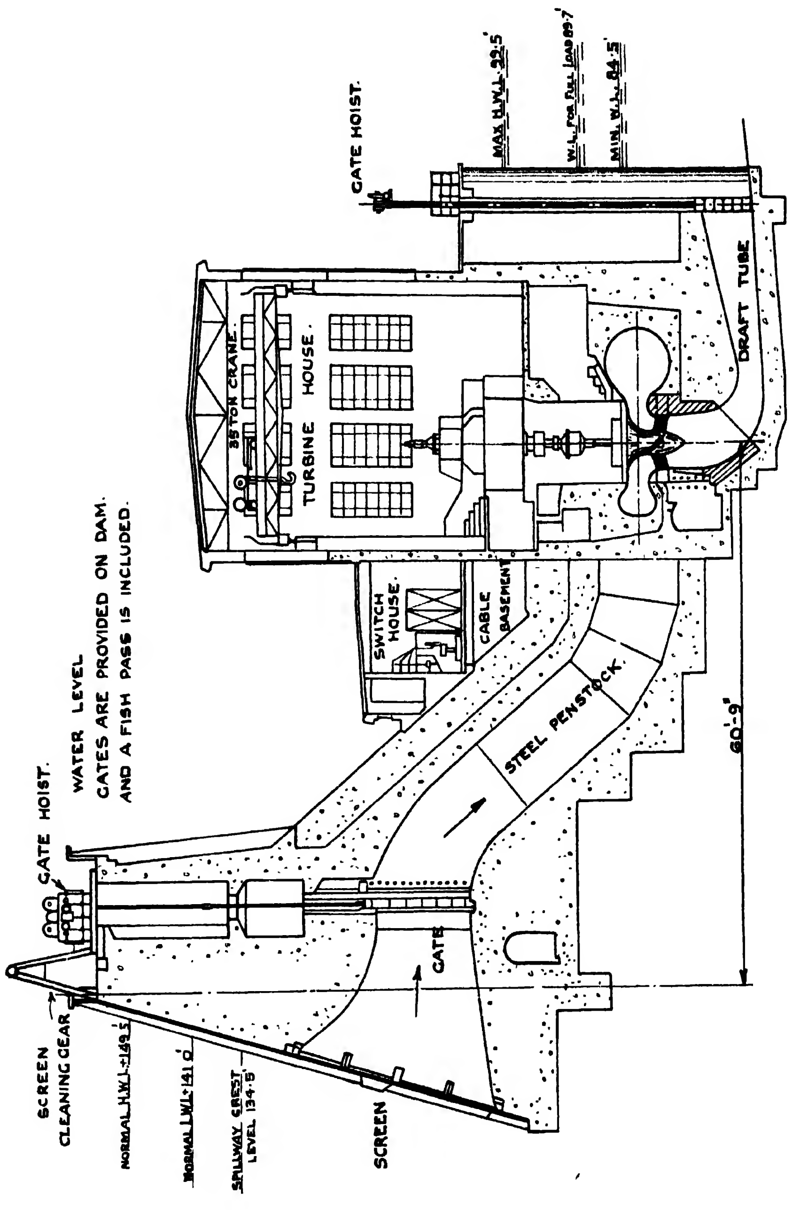

FIG. 602. 4 MW Kaplan Turbine Setting.

upper limit approaching 400 ft. For larger machines such a casing becomes subject to considerable deformation, and requires bracing unless supported throughout by a heavy mass foundation.

For higher heads, cast-steel spiral casings are usual. The velocity at scroll entrance varies from about $0{\cdot}15\sqrt{2\,g\,.\,h}$ for low heads to $0{\cdot}12\sqrt{2\,g\,.\,h}$ for high heads.

For vertical machines the pipe-line usually approaches the wheel on its horizontal centre line, but with the end of the scroll entrance offset laterally, so that the far wall of the pipe-line becomes the outside wall of the spiral case. On most installations the scroll entrance is smaller than the pipe-line; consequently a taper pipe is required, and it is usual to insert a valve or penstock gate at this point.

For heads over 250 ft., and where large machines are required, it is advantageous to use a cast-steel casing as it is stiff and contributes to the stability of the sub-structure. Further, it can be shop assembled and tested under pressure, and there is little difference in total cost. Steel-plate casings have to be tested *in situ* after all riveting or welding is done, *e.g.*, for a head of 105 ft., a pressure of 90 per sq. in. was applied. To enable this to be done, the inlet to the spiral casing and the outlet to the runner were closed off with special test covers. The spiral casings must be kept at the works until the turbine is completed.

Where runners have a relatively small discharge under high heads, a horizontal setting may be desirable, chiefly on account of the improved accessibility. The pipe-line normally approaches the runner from below at the level of the scroll entrance, thus necessitating the turbine and alternator shaft being placed parallel to the length of the turbine house.

The turbine and alternator may also be placed with the shaft at right angles to the length of the turbine house, should the pipeline run the length of the turbine house under the machines, with upward branches to each machine.

Figs. 599 to 602 show typical settings.

Auxiliary House Sets. To avoid suction and pressure surges, these sets are usually arranged to discharge into a sump. Difficulties are often experienced in fixing the final discharge to the tail-race, as any noticeable disturbance of the water is liable to attract the fish to it. In one scheme a difficulty was that of the excavation entailed in taking the discharge from the auxiliary sets underneath the overflow pipe from the surge tower, and it was

suggested that this could be met by taking the discharge through the overflow pipe and streamlining it.

Draft Tubes. On leaving the discharge side of the runner, the water possesses potential energy due to its elevation and, on account of its velocity, kinetic energy.

The primary function of this tube is to permit the placing of the turbine at a level above that of the water in the tail-race under high-water conditions of the river. In this way no loss of effective head is incurred due to its elevation, and, at the same time, a large part of the kinetic energy of the water leaving the runner is recovered by giving the tube a suitable taper. To ensure that as little energy as possible is left in the water as it discharges into the tail-race, the draft tube tapers gradually towards the outlet. The velocity of the water is thus gradually reduced, and it discharges smoothly into the tail-race.

With low specific speed turbines this recovery is not of such importance, but on high specific speed machines, up to 25 per cent. of the energy of the water may be recovered in the draft tube. In view of this the design and efficiency of the tube is of considerable importance. With a parallel tube discharging vertically into the tail-race, the whole of the kinetic energy is lost, but by gradually increasing the diameter so as to obtain a gradually reducing velocity, a consequent reduction in loss of energy is effected. The draft tube operates under suction, and submerging the lower end of the tube prevents air from entering and destroying the vacuum.

The vertical flaring tube used in an open runner pit necessitates the floor of the pit being reinforced to carry the load of the runner, alternator, etc. In most cases each machine will occupy a bay with concrete piers separating adjacent bays. The spacing of the machines is usually determined by the permissible flume velocity above the runner, and such a layout will often give a satisfactory tail-race velocity with a reasonable depth of the race.

The area at the top of the tube will be the same as that of the runner to avoid shock, and is of circular cross section. The velocity at the runner outlet varies from 0·4 to $0{\cdot}5\sqrt{2g \, . \, h}$ for low head and high speed, to $0{\cdot}12\sqrt{2g \, . \, h}$ for high head, slow speed. The exit velocity of the draft tube usually varies from $0{\cdot}1\sqrt{2g \, . \, h}$ to $0{\cdot}02\sqrt{2g \, . \, h}$ for low and high heads, respectively.

In fixing the elevation of the tube, the following must be allowed

for :—the depth of the runner below head water level; the height of the runner gate pit and turbine house basement or equipment above the tail-race flood level, and the length of the draft tube necessitated.

The elevation of the mouth of the tube will be fixed for a given area by the minimum tail-race water level after allowing a suitable seal or depth of water (2 to 3 ft.) over the upper end of the tube. A manhole and also a small drain pipe are usually provided in the vertical flaring tube. This drain pipe permits the space above the runner hub to be emptied into the tube, and so reduces the thrust on the runner.

To reduce excavation with machines of large discharge capacities, the elbow type of draft tube is used. This type is usually arranged so that its cross-section is gradually changed from circular at the runner outlet, to elliptical at the mouth of the tube. By curving the tube so that it discharges in the direction of flow in the tail-race, the kinetic energy is thus utilised in assisting this flow and is not entirely wasted. The velocity at the mouth may be appreciable, and a velocity-head loss of approximately 0·6 to 0·8 ft. head is usual. Various other forms of tube are in use, but constructional difficulties generally outweigh their advantages.

The draft tube (on very low falls about 2 or 3 ft.) may theoretically have a suction of approaching 30 ft., but in practice it seldom exceeds 20 ft. Even so, unless it is perfectly airtight, there will be a loss of efficiency. It has been stated that the admission of air to the draft tube helps to steady the flow of water when the turbine is operating on low loads. If no air is admitted under these conditions it is contended that there is a considerable disturbance in the water leaving the runners, and an objectionable noise is produced in the draft tube. At high elevations, with the barometer at 22 or 23 in. Hg., the suction should be reduced proportionately, as well as in very large pipes.

The maximum practical elevation depends on the diameter of the draft tube, and typical figures are as follows :—

Diameter of tube, ft. .	1·0	3·0	8·0
Elevation, ft. . . .	30·0	23·5	14·0

The head equivalent to the velocity of flow down the tube should be deducted from these figures. High efficiencies of low-head machines have been made possible due to careful attention in draft tube design.

A flaring or conical tube improves the speed regulation; as with rapid regulation on a falling load the inertia of the suction column tends to break the column and so produce a vacuum in the machine casing. Such a separation may be followed by a reflux up the tube, and give rise to water hammer. A small change of load may, with a long tube, set up pulsations which upset running conditions, but which would be minimised with a conical tube. Usually the tube consists of an outflow bend and an upper taper pipe constructed of mild steel plates electrically welded together. To reduce eddies and recover the maximum amount of energy, the lower portion of the tube has a streamlined dividing wall built up of steel plates and beams. The web across the draft tube bend may have a definite value from the point of view of efficiency, but in some cases it is only for the purpose of rigidity. The tubes are sent to the site in sections and after being placed in position are finally embedded in the reinforced concrete structure. After concreting, holes can be drilled in the plates and liquid grout is then forced in to fill any voids. The holes are plugged and the inner surfaces of the tube are ground to a smooth finish.

The outlet of each elbow type draft tube is usually provided with a sluice gate, so that the tube can be isolated for inspection.

Governors. The function of the governor is to adjust automatically the turbine gate or nozzle opening to meet load conditions and thus attain speed regulation. A change in load causes a change in velocity and momentum of the water column, and if it varies quickly pressure fluctuations will take place. If a sudden change from full-load to no-load is accompanied by a governor failure, the speed would rise to about twice normal. It is not practicable to check this by means of an emergency governor, and the machines must be capable of running safely, for a short time, at this overspeed. With Kaplan turbines a speed approaching three times normal is theoretically possible. The turbine designer fixes the closing time of the turbine regulator for a sudden change from full load to no load, taking into account the increase in hydraulic pressure and he requires a certain minimum inertia to ensure stability of the governor. The electrical designer, on the other hand, endeavours to limit the peak transient speed when full-load is thrown off. The speed itself is of no importance, as the alternator has to be designed for the much higher steady overspeed which occurs when full load is thrown off and the speed regulator fails to operate. The running up time of the alternator must first be considered;

this is the time required to run up the machine from standstill to full speed when applying the normal full-load torque. The running up time is proportional to the inertia and to the square of the speed, and inversely proportional to the output in kW.; it is of the order of 6 to 10 seconds.

A governor should secure a sensitive and positive control without any danger of either overrunning or of hunting.

The governor may also be arranged to operate a relief valve or a jet deflector, and thus prevent an undue rise of pressure in the pipe-lines should the load be suddenly thrown off a turbine.

A governing device which does not employ deflection or by-pass arrangements can be used to regulate the power delivered to the wheel. This device is a form of diffuser and consists of vanes on the conical needle which enter the jet orifice. When the mechanism forces these vanes to protrude they break up the jet into a hollow cone, and the energy imparted to the turbine wheel is quickly destroyed. In this way very small forces are able to govern the largest machines of this type, and regulation in cases of complete dropping of load from 100 per cent. to zero can be as close as 3·9 per cent. Braking of wheels is obtained by a counter jet which throws a stream of water on to the back of the buckets, an additional nozzle being provided for this purpose.

The principal performance characteristics are:—sensitiveness; stability; freedom from hunting or racing; capacity; speed regulation and regulating time.

Speed regulation is dependent upon the following:—

(1) Flywheel effect of the revolving parts of the turbine and alternator.

(2) Variation in effective head acting on the turbine.

Speed regulation is usually expressed in terms of a ratio and with reference to two extremes of load.

N_1—r.p.m. for load "A" (higher speed).
N_2— ,, ,, ,, "B" (lower speed).

Then speed regulation between loads "A" and "B" $= \dfrac{N_1 - N_2}{\left(\dfrac{N_2 + N_1}{2}\right)}$

$$= \frac{N_1 - N_2}{N}.$$

Where N is the arithmetical mean of the two extreme speeds, this ratio is expressed as a percentage. The speed regulation is achieved by altering the gate or nozzle openings of the turbine, and therefore the quantity of water, by means of an automatic governor. The essential features of a governor are :—a speed-responsive device ; a compensatory device ; relay apparatus ; valve mechanism ; regulating cylinder ; oil pressure pump and pressure tank, etc. The oil pressure is at 150 to 200 p.s.i.

A safety governor of the steam turbine type is located on the main shaft. The ancillary equipment associated with governors varies with the different types and the degree of control desired, but the following are typical :—

(1) Control of turbine speed from the control room.

(2) Overspeed tripping device ; independent of main governor.

(3) Emergency tripping device—at turbine and from control room.

(4) Oil pressure failure.

(5) Manual control to open and close turbine gates.

(6) Device to prevent turbine gates moving from the closed position.

(7) Adjustable stop to limit opening of gates.

(8) An unloading valve to enable pump to operate against a small pressure and so save power when turbine load is steady and the Servo-motor has little work to do.

(9) A small three-phase alternator on the shaft of the main alternator, which operates a self-starting synchronous motor to drive the pendulum.

It is not usual to provide all the above equipment, but some are indispensable.

Speed and Efficiency of Turbines. The principal factors affecting the speed are available head and output required. For a given output the speed falls with the head, and for a given head the speed falls with increase in output. Turbines with large outputs and low heads therefore operate at slow speeds. With constant speed and constant head the efficiency of reaction turbines falls rapidly as the load is reduced, and it is therefore desirable to operate them as near full load as possible. This may be obtained by dividing the total output among a number of machines, so that load variations can be met by varying the number of machines connected to the bus-bars.

The characteristics of the Kaplan turbine make it economical

to use fewer and larger machines, and have resulted in an increase in size of vertical shaft machines.

There is a critical speed at which any turbine operates under the most economical conditions, and if this speed is exceeded without a decrease in the diameter of the runner or wheel, the efficiency is reduced.

The peripheral speed has a relation to the theoretical velocity of the water falling freely through a height equal to the distance

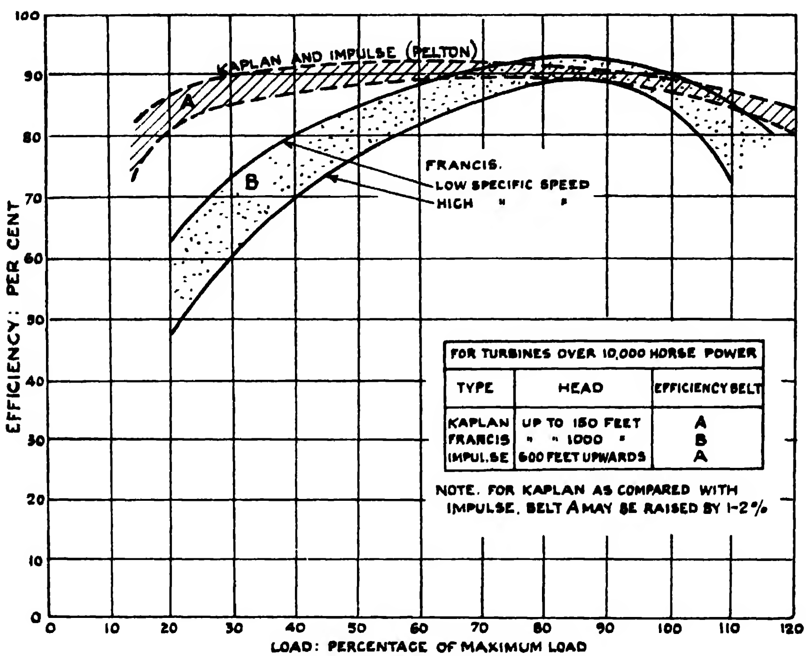

Fig. 603. Typical Efficiency Belts for Turbines.

between the head-race and the tail-race levels. The peripheral speed varies from 60 to 80 per cent. of the theoretical water velocity for reaction turbines, and 40 to 50 per cent. for impulse turbines.

Performances of turbines of varying sizes operating under different conditions can be compared by reference to "specific speeds." This expression denotes the speed of a geometrically similar model of the turbine under construction, designed to give an output of 1 B.H.P. under a head of 1 ft. It is a figure which

gives a fundamental basis of comparison between turbines of different types.

$$\text{Specific speed } N_s = \frac{N \cdot \sqrt{P}}{4\sqrt{H^5}}$$
$$= \frac{N \cdot \sqrt{P}}{H \cdot \sqrt{\sqrt{H}}}$$
$$= N\sqrt{P}/H^{5/4} = \frac{N.\sqrt{P}}{H^{5/4}}$$

P = B.H.P., H = head in ft., N = speed r.p.m.

For given values of N and H the output is proportional to the square of the specific speed, while for a given head and output, the actual speed of the turbine is proportional to its specific speed. Francis turbines of large capacity with low specific speeds have been used for heads up to 600 ft., instead of Pelton wheels. Ordinary ranges of N_s are :—

Impulse	3–6
Reaction	10–110
Propeller	110–225

Fig. 603 shows typical efficiency belts for turbines. A specific speed above 7 for the impulse turbine and below 20 for the reaction turbine may represent a marked decrease in efficiency. Typical maximum specific speeds are shown in Fig. 604.

Relief Valve. A relief valve or pressure regulator is attached to the turbine casing or the pipe-line near the turbine in such a way that when the turbine gates are closed suddenly and a sufficient amount to disturb the regulation on account of pressure rise, the relief valve will be opened by the governor and so maintain the pressure rise within desired limits. If the discharge capacity of a relief valve is sufficiently large, the pressure rise can be limited to a small value.

To prevent the water discharging from the relief valve doing damage to the tail-race, the outlet can be fitted with a disperser.

Should it be necessary to drain a tunnel or pipe-line when there is no load, this can be done through the relief valves fitted to the turbines and have the same capacity as the turbine runners. They are fitted with dispersers and are capable of discharging continuously without damage either to the plant or to the tail-race.

Total loss of load is possible by opening the main circuit-breaker, and it may be advisable to install a relief valve or pressure regulator

for the protection of the pipe-line without regard to any improvement in speed regulation.

Thrust Bearing. In addition to carrying the weight of the alternator rotor, this bearing has to support the weight of the turbine runner and shaft and the hydraulic thrust.

In vertical machines much of the load on this bearing comes from the turbine. In a large Kaplan, about 60 to 65 per cent. of the total load might represent the weight of water acting on the runner. In low-head Kaplans the hydraulic load varies very little between no-load and full-load. An appreciable upward thrust can occur with a Kaplan or propeller turbine only if the water flow is reduced too rapidly following loss of load.

Total thrust-bearing loads of up to 1,350 tons obtain in practice. In the umbrella design, the thrust and guide bearings are immediately below the rotor. This arrangement has several advantages over the design in which there are two guide bearings and the thrust bearing is above the rotor. Among these advantages are easier access to the rotor for inspection or dismantling, lower overall height (which permits a reduced height of turbine house), a simpler lubrication system, and smaller bearing loss.

A high degree of flatness and finish is given to the face of the thrust collar by lapping. To give the necessary degree of flexibility, the thrust bearing pads are supported on short springs each of which is pre-compressed by means of a screw and nut. This pre-compression limits to a small amount the change in the length of the spring between no-load and full-load, but provides sufficient flexibility to allow the pads to tilt slightly at starting and so assist the formation of an oil film between them and the thrust face. The thrust bearing is oil immersed and is self-lubricating, the oil being cooled by continuous circulation through a water cooler external to the alternator. This arrangement is considered to be preferable to putting water coolers in the thrust bearing reservoir as the coolers are more accessible ; thrust-bearing housing can be made smaller ; access to thrust pads is easier ; less risk of water accumulating in the thrust-bearing housing through failure of a cooler tube ; and cleaning of the oil is facilitated. A motor-driven pump delivers cooled oil to the bearing reservoir and from there it drains back to the sump tank. The oil is cleaned by passing through a strainer. The pump and cooler are in duplicate, and automatic controls ensure that in the event of failure of the oil supply, the stand-by pump is started and an alarm signal given. One design has the thrust pads

contained in an oil bath without any oil circulating system. Cooling is effected by water which flows through tubes immersed in the oil.

Guide Bearing. This may be situated immediately above the thrust bearing and the journal formed on the upper cylindrical part of the thrust collar. For ease of assembly and dismantling, the bearing—which is white-metal lined—is made in halves. A supply of oil is fed to the guide bearing from the main supply to the thrust bearing reservoir. In the event of this supply failing, the guide bearing is kept lubricated by oil supplied to it centrifugally through ducts in the thrust collar. Oil flow indicators, having electrical contacts, are arranged to give warning in the event of the oil flow falling below a given rate in the supply pipes to the thrust and guide bearings.

Brakes. Owing to the high moment of inertia of large machines they may take half-an-hour to come to rest. To expedite slowing down, a set of brakes, which act upon a removable brake track on the rotor rim, can be included. The brakes are intended to be applied at about half to quarter speed when the machine is being shut down. Their purpose is not merely to reduce the time taken for the machine to come to rest, but also, by increasing the rate of retardation at low speeds, to reduce the amount of wear that can take place in the thrust bearing during the last fraction of a revolution after the oil film has broken.

The brake shoes are " Ferodo " lined, and each is attached to a piston sliding in a small cylinder and operated by oil-pressure. Smooth application of the brakes is ensured by the use of compressed air to apply pressure to the oil in the brake cylinders. A motor-driven compressor is provided with a receiver capable of serving all machines in the station. In addition to their use for bringing rotors to rest, the brakes can also be used as jacks for lifting the entire rotating system of the alternator and turbine. For this duty, they are supplied with oil at about 800 p.s.i. from a small motor-driven pump associated with each machine. The primary purpose of lifting the rotor is to enable the thrust bearing pads to be removed for inspection, but arrangements can be made whereby lifting the rotor may be carried out as a routine measure before starting the machine, in order to admit oil to the thrust bearing surfaces and so reduce wear. The high pressure oil pump is started and the rotor gradually begins to rise on the jacks. When it has risen $\frac{1}{8}$-in. a limit switch on the shaft stops the pump automatically and lights an indicating lamp. The oil in the jacks

is then released by opening a by-pass valve, and the rotor returns to its original position. Precautions are taken to minimise incorrect operation.

In some designs the mechanical brake on the alternator can be applied at full speed with the gate closed.

For Pelton wheels a small nozzle is used to apply a jet of water against the underside of the buckets and quickly brings the machine to rest. Another method consists of a curved duct arranged in the casing opposite the nozzle and the entrance of this duct lies in the

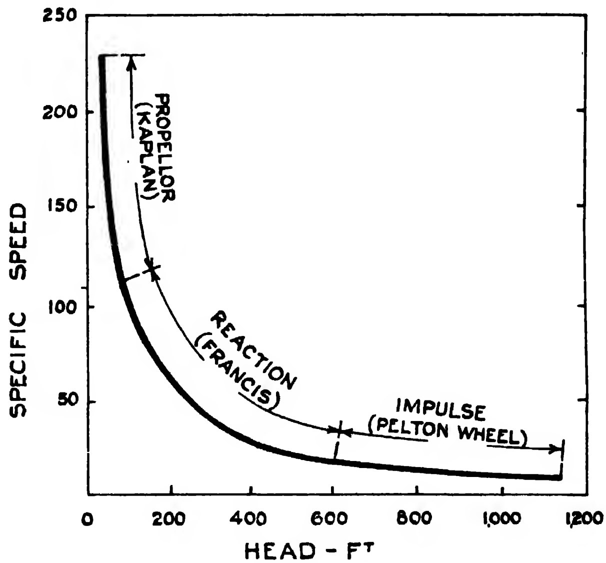

FIG. 604. Typical Maximum Specific Speeds.

projected path of the water jet, its exit being directed against the back of the buckets. The entrance of the duct is sealed by a bursting diaphragm which is so proportioned as to withstand the action of the spray water hitting it, but to burst open by the portions of the jet passing unused through the buckets at a given overspeed. Portions of the water are directed by the duct against the back of the rotating buckets to exert a powerful braking action on the runner. The runaway speed of an impulse turbine may be 80 per cent. of the normal speed but can be reduced to 60 per cent. or less of the latter thus reducing the excess stress in the runner, buckets and fixtures. It should be possible to make impulse turbines up to 140 MW for a speed of 300 r.p.m., instead of 200 r.p.m. normal working.

Capital costs of both turbine and alternator should be reduced. An anti-racing device has been used on propeller type runners, which consists of a number of slanting vanes placed immediately above the runner hub. The vanes are normally retained flush with the outer circumference of the hub by springs, or braking pins within the hub. At some pre-determined speed, usually about 55 per cent. above normal, the vanes are projected simultaneously outward into the water vortex above the runner blading and, in combination with the latter, exercise a powerful braking effect.

Shaft Coupling. There are many designs available, and in one arrangement the torque is transmitted by a single diametrical key of ample proportions. The coupling bolts are locked and are not relied on to transmit the torque.

Oil Pumps. The oil supply is usually afforded by a mechanical pump gear-driven from the main shaft, and there is also an electrically-driven pump which floods the bearing before starting the machine. When the machine is up to normal speed and the shaft pump is working, an oil pressure relay shuts down the electrically-driven auxiliary pump. This pump starts automatically in the event of failure of oil supply from the shaft pump.

ELECTRICAL PLANT

The principal items of plant are :—Alternators, exciters, switchgear, transformers, reactors and batteries.

With the exception of the water-driven alternators and exciters, the remainder of the plant is similar to that installed in steam electric power stations. The same principles generally apply in respect of hydro-electric power stations.

Main Electrical Connections. It is necessary to prepare a diagram (Fig. 605) of the principal electrical connections, which should provide the following features unless special local considerations make it such that some are unnecessary :—

(*a*) Bus-bar arrangements to be such that the alternators and transformers can be operated under the most efficient conditions according to the loads obtaining.

(*b*) Arrangements should facilitate the disconnection of any alternator, transformer, circuit-breaker or circuit, without interfering with the normal station output, for the purpose of inspection, maintenance, repair and testing.

(*c*) Short-circuit conditions should be maintained within specified limits either by way of grouping or the provision of reactors.

(*d*) Protective equipment of proved performance should be provided in accordance with plant and other apparatus protected.

(*e*) Afford a reliable and adequate supply to the essential station auxiliaries.

(*f*) The necessary metering, synchronising and other control apparatus should be provided.

Alternators and Exciters. The fundamental difference between steam and water turbo-alternators is the relatively slow speed of

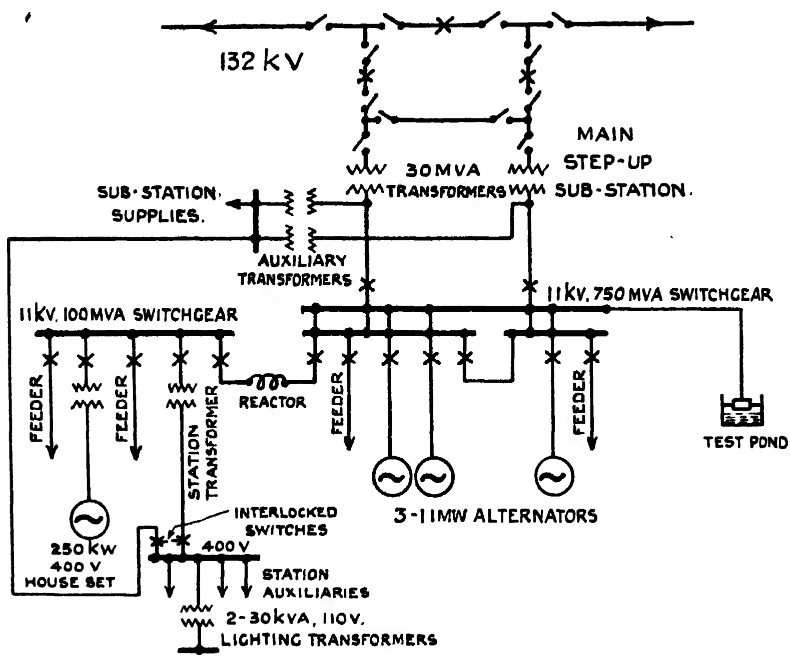

FIG. 605. Main Electrical Connections.

the latter, while at the same time the inherent danger of high run-away speeds has to be guarded against. The electrical rotors are usually of the salient pole type. The electrical characteristics such as reactance, short-circuit ratio, and permissible temperature rise do not affect the dimensions unduly, for in a machine of large diameter and slow speed the amount of electro-magnetic material can be varied to suit conditions required. The rotary parts embody a flywheel effect greater than usual, to ensure satisfactory governing, and the rotors should be capable of withstanding the stresses produced when running at maximum overspeed. The lowest critical

speed of the rotating system should be above the maximum overspeed.

If the alternator is placed on a concrete pedestal, it is necessary to provide a door in the pedestal to afford access to the wheel gate mechanism, and possibly openings for ventilation, governor pumps and exciter. In the design of this pedestal, full allowance should be made for impact loadings and runner thrust, together with the electro-magnetic forces which may be set up under short-circuit conditions.

Open type alternators are cheaper, and draw air from below and deliver it into the turbine house. The closed air system is best from the point of view of appearance both inside and outside the station. It also avoids discharge of a large quantity of warm air into the turbine house, makes the station quiet, and reduces the amount of moisture which might, on the open-circuit principle, be passed through the alternator during the wet and humid seasons.

The closed air system is chiefly used for the larger machines, and approximately 100 cubic ft. of air per minute is required for each kW. of loss in the alternator. The air velocity in the ducts is usually between 1,000 and 1,500 ft. per minute.

The ventilating system may include fire-fighting equipment of carbon-dioxide gas, and, in some installations, water spray pipes are provided in the end winding enclosures which can be put into operation as a last resource. The gas installation is in some cases of sufficient capacity to reduce the combustion content of the gases within the alternator enclosure below 66 per cent. with the output of the initial group of cylinders.

The ingoing air for open type machines is cleaned by a viscous air filter. To enable the air circulation to be stopped in case of emergency, electrically-operated dampers can be provided in the inlet and outlet ducts.

The stator is built up of welded steel plates, and may be made in, say, four parts to facilitate transport. In one design the stator core is built of silicon-alloy laminations punched in segments, each segment being secured by a half-dovetail notch in its two outer corners engaging with a corresponding " dovetail " bar welded into the stator frame. The stator winding is placed in open slots and is of the two-layer diamond-coil type, all the coils being duplicated and interchangeable. Each coil consists of a single turn made up of a number of copper strips in parallel, each strip insulated with glass braid, the copper strips are transposed to reduce circulating current

losses. The principal insulation of each coil consists of mica-silk tape, consolidated by vacuum drying and impregnation under pressure with bitumen gum. The coil ends are corded to an insulated steel bracing ring which is supported from angle brackets carried on the core end plates.

The Roebel bar winding, in which each single bar is made up of a large number of parallel strands transposed in the slot but brazedor soldered together at each end is also used. Difficulties are likely to arise if the output per pole is relatively small, owing to the large number of slots required, and it is necessary to use a double-layer multi-turn coil winding. Satisfactory transposition of the strands in this winding can be obtained by inversion of one or more turns in the end windings. These windings have the advantage that transient voltage rises at the alternator terminals do not produce a voltage rise across adjacent strands, and it is not essential to use expensive materials such as glass or mica to insulate the strands. Impregnated-asbestos insulation in these windings has proved entirely satisfactory.

The rotor has a laminated steel magnet wheel rim, on the periphery of which the poles are mounted. The rotor usually has to provide a very large fly-wheel effect to ensure satisfactory speed regulation of the turbine under conditions of varying load. The laminated construction of the rim enables the heavy mass of metal necessitated by this requirement to be built into the rotor, and avoids the difficulties which the use of castings involve. The laminations are punched in segments and the successive layers are overlapped to give adequate strength to the completed rim. The assembled laminations are clamped between heavy steel end-plates by a large number of fine clearance bolts. Fitted bolts are unnecessary, as the frictional forces are such that the laminations cannot slip relatively to one another, even at the runaway speed. The rim is carried from a central cast steel hub by a suitable number of welded steel arms. The field poles are built up of heavy gauge steel stampings clamped between semi-circular cast steel end-plates by bolts. Both stampings and end-plates are formed with a T-shaped projection which engages with a corresponding slot punched in the periphery of the rotor rim.

The field coils are former wound of copper strap bent on edge. The size of the strap and the number of turns being chosen to give full-load flux with the given excitation and voltage. Asbestos is used for the insulation between turns; the insulation between

the core and the pole body is of flexible Micanite built up on a strong cloth backing. During manufacture the coils are hot pressed to ensure that no subsequent shrinkage takes place. The field coils, when assembled on the poles, are supported all round their periphery by the overhanging tip of the pole punching, and end-plates are firmly clamped between this tip and the magnet wheel rim. In some machines, damper windings are fitted in the pole faces to increase the stability under system disturbances, and reduce the risk of over-voltages in certain conditions of unbalanced short-circuit on long open-ended high voltage transmission lines. The principal disadvantages of a damper winding, apart from its cost and complication, are the slightly increased losses on load, and the increased fault currents that result from the lowering of the sub-transient and negative-sequence and zero-sequence reactances. With long transmission lines of high capacitance, the advantages are considered to outweigh their disadvantages, although many machines are operating satisfactorily without them. They are said to be beneficial in damping out any oscillations due to variation between blade setting of the Kaplan turbine and the movement of the gates. Some designs have the damper windings on the poles only, without interconnections from pole to pole of the short-circuiting strips. The amount of over-voltage in certain conditions of unbalanced short-circuit tends to be less if the damper winding is connected between poles, but from the point of view of stability there is usually little gain. Damper windings are unnecessary in solid pole-shoes. They are useful for automatic synchronising purposes.

One of the largest machines (Metropolitan-Vickers Electrical Co. Ltd.) built in this country has a rated output of 30 MW (33·33 MVA.) at 0·9 lagging power factor, 11 kV., 3-phase, 50 cycles per second. It is capable of an output of 16 MVA. at zero leading power factor for line charging, the normal speed being 166·7 r.p.m. (36 poles), but the rotors are designed to withstand a maximum overspeed of 410 r.p.m. The overall diameter is 34 ft., and weight 330 tons, the rotor weighing 182 tons.

Electric heaters (about 10 kW.) of the tubular type can be fitted inside the alternator casings to maintain the temperature above the dew point when the machines are standing. These are controlled by thermostat and contactor in such a way that they are switched on and off according to the temperature.

An alternator is a very high efficiency machine, and the information given under steam turbo-alternators will apply in most cases to

water-turbine-driven alternators. Table 98 gives data relating to a 10·5 MW, 11 kV., 250 r.p.m. water turbo-alternator.

TABLE 98

Load . . . . per cent.	40	60	80	100
Iron loss . . . . . kW.	102	102	102	102
I^2R + Stray losses . . kW.	15	38	75	117
Excitation . . . . . kW.	28	36	47	60
Friction and Windage loss . kW.	97	97	97	97
Exciter loss . . . . kW.	6	7	9	12
Total loss . . . kW.	248	280	330	388
Output . . . . . kW.	4,200	6,300	8,400	10,500
Input . . . . . kW.	4,448	6,580	8,730	10,888
Efficiency . . . per cent.	94·5	95·7	96·3	96·5

These machines usually have a relatively large number of poles and relatively few armature turns per pole, and, in consequence, tend to have high transient and sub-transient reactance. Typical figures (" per unit " values) for large vertical machines are :—

	With Damper Windings	Without Damper Windings
Sub-transient reactance	0·19 to 0·30	0·23 to 0·37
Transient reactance	0·25 to 0·40	0·25 to 0·40

The synchronous reactance is usually in the region of 1·00 to 1·3 (per unit) or 100 to 130 per cent.

Considerations of system stability rarely permit 1·3 to be exceeded, but values of 0·5 may be necessary when alternators operate in parallel at opposite ends of a long transmission line. The steady-state stability of a system depends on the total reactance, including that of the transformers and the transmission line, and not only the synchronous reactance of the alternators. In one station 16kV alternators are designed with low reactances because of the very long-distance transmission which approaches 1,900 miles. The sub-transient reactance is 15 and the transient 22 per cent.

The turbine designer in fixing the value of the flywheel effect, which the alternator is expected to incorporate in the rotating parts (the turbine inertia is negligible), uses the formula :—

$$W\,k^2 = \frac{5{\cdot}95 \;.\; 7{,}160 \;.\; \frac{1}{2}\,m\,v^2 \;.\; P}{N^2} \text{ lb. ft.}^2$$

Where N is the speed in r.p.m. and P the B.H.P.

The various values of the flywheel effect obtained from this is chiefly due to variations in turbine speed regulation and pipe-line pressure limitations for different schemes. The average of the expression $\frac{1}{2} m v^2$ appears to be about 270, but varies from 157 to 407.

A reliable D.C. supply is required for the alternator field windings, the extent of the supply depending upon the speed, electrical load and the power factor. The excitation required is greater with low speed, low lagging power factor and large load.

The principal requirements of an excitation system are:—reliability, simplicity, economy of operation, reasonable initial cost

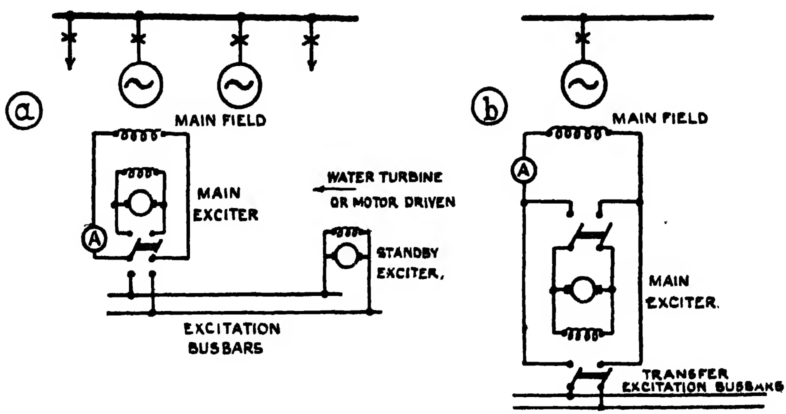

FIG. 606. Excitation Systems.

and adequate reserve capacity. The drive should be sound; cabling and wiring associated with the circuits should have ample capacity, have high grade insulation and be carefully routed and supported. The insulation should be capable of withstanding up to ten times the normal excitation voltage in order to deal successfully with transient voltages resulting from alternator short-circuits.

Excitation systems (Fig. 606) can be broadly grouped under three heads:—(1) Centralised, (2) Individual, and (3) Direct-drive. The first system has advantages in that a small number of comparatively large exciters may be used, and that a stand-by battery can be floated on the bus-bars. The independent unit permits of shorter and simpler cabling and connections. It is possible to use water turbine or motor-driven (or a combination thereof) exciters for the first and second systems.

The direct-drive from the main machine is very efficient, reliable, simple and convenient, and, except for very slow speed machines, inexpensive. Each direct-driven exciter can be of sufficient capacity to serve two alternators. A main and pilot exciter are usual on large machines. The main exciter has two opposed field windings both of which are energised from the pilot exciter. The negative winding is in series with a constant resistance, and the positive winding in series with a motor-operated rheostat, having a large number of steps, which is controlled by an automatic voltage regulator. The main exciter has a ceiling voltage equal to twice the normal excitation voltage, and a rapid rate of response equal to the normal voltage per second which is obtained by opening the negative field. The pilot exciter is compound wound.

Some of the disadvantages are :—exciter troubles put the machine out of commission, and the alternator voltage is subject to speed fluctuations. Slow-speed exciters do not respond quickly to automatic voltage regulators. Main field excitation from a permanent-magnet type governor alternator and a rectifier may also be possible, but undue variations of voltage during field forcing would have to be avoided. In some stations separate synchronous motor-driven exciters are provided so that they may have full excitation at zero speed when an alternator is required to bring up to speed with it, say, large pumps. One installation has 400 kW., 250 volt exciters driven by 600 H.P. 6·6 kV. synchronous motors operating at unity power factor. It is generally possible to interchange rotors and to use an exciter with any rotor, but it is not possible to change stators, owing to the impracticability of providing satisfactory jigs on account of the large diameters of the stators. Spare parts are in general interchangeable.

Overload on alternators is usually possible with a consequent reduction in the factor of safety. Under such conditions the exciter is the limiting feature, and this can be met if the interconnected steam stations deal with the majority of the wattless current, thus allowing the power factor of the hydro-sets to be raised.

On electrical systems having very long transmission lines, the alternators may be operated over-excited, or a spare machine may be run as a synchronous capacitor, to counterbalance the effect of line reactance. A power factor meter, or a reactive volt-ampere meter, which is essentially a wattmeter connected to indicate the idle instead of the effective watts, can be used to show the conditions obtaining. If an alternator is used as a synchronous capacitor,

two integrating wattmeters are used to record the output. The instruments have restraining pawls, so that one integrates generated power and the other power taken when motoring. When alternators are used as synchronous capacitors, the plant can be so arranged that the turbines can be run either coupled or uncoupled from them.

In one station having 20 MVA., 500 r.p.m. machines, dual-purpose exciters are mounted on the shaft extension. The nominal voltage is 11 kV., but the machines are designed to operate continuously over a wide range of voltage, and up to a maximum of 12·5 kV. for short periods. The excitation of the machines is controlled by automatic voltage regulators of the Tirrell type, working in conjunction with under-excitation and super-excitation relays. The maximum kVA. rating can be supplied down to a power factor of 0·65 lagging, and at zero power factor the rating is 14 MVA. The conditions of demand entail the supply of high charging currents during low-load periods, and the alternators are designed to be stable under the most exacting conditions.

One American station has 108 MVA., 120 r.p.m. machines, which provide sufficient charging capacity and stability to enable a single machine to energise a 250-mile 220 kV. line, and, further, to maintain synchronism through a double-line ground fault at the end of the line if it clears in not more than 0·013 second. In another station, the 21·5 MVA., 11/13 kV., 0·8 power factor, 3-phase 50-cycle machines are designed to withstand a maximum voltage of 15·6 kV. for five minutes. This extra rating safeguards the machines during the period before the field suppression can act, which may happen in the event of excessive speed variation resulting in abnormal electrical conditions. The rating is obtained down to a power factor of 0·65 leading, and for line charging purposes, the machine can deliver 15 MVA. at zero leading power factor.

Auxiliary Power Requirements. Auxiliary power is required for head gates, screens, sluice gates and valves, locks, air compressors, oil pumps, ventilation fans, heating, lighting, forebay ice protection, battery charging, and perhaps exciter drive.

The total power for auxiliaries may vary from 1 to 5 per cent. of the station output, and this power is usually obtained from station transformers, unit transformers, and, in larger stations, from auxiliary house sets.

House sets can be driven from the main machines or by small

independent turbines, and motor drives are also satisfactory. A small set can be installed to assist in affording a supply during the construction period, and be subsequently used as a house set. A tertiary winding on the main step-up transformer is a simple arrangement and ensures an auxiliary supply without direct connection to the main higher voltage switchgear. If two station transformers are installed and only one is normally in circuit, then, in the event of failure, an alternative supply can be automatically switched from the other transformer. In some stations no D.C. auxiliary equipment is used, thus eliminating the overloading of the storage battery in the event of complete power failure. An emergency supply to auxiliaries is afforded by a Diesel engine set. If the essential plant depends entirely on the operation of electrically-driven auxiliaries, these should receive a supply from an independent source of power. The voltage regulator may account for up to some 20 per cent. of the cost of a small house set. It would appear that 400 volts is better than 3 kV. for the auxiliary sets, as it enables a plain diamond winding, with two bars per slot, to be used. There is, however, no difficulty in winding small machines for 3 kV., but it means an increase in price. The division of auxiliary power can be arranged so that the essential auxiliaries are supplied from the unit transformer, and the general purpose ones from a station transformer, as follows :—

Unit transformer: Governor pump; cooling water pump; alternator ventilating fans.

Station transformer: Crane; motor-generator or rectifier; valve oil pump ; de-watering pump ; lighting and heating.

If the governor oil is delivered from motor-driven pumps taking their supply from the main system, it is desirable to have an auxiliary turbine-driven pump, or an alternative supply. This enables the turbines to be started if the station is completely without a supply.

Electrical Governor Control. In one system of control, a small (1 to 5 kVA.) permanent-magnet, three-phase alternator is mounted on the main alternator shaft, below the exciter, and supplies the power to a motor-driven actuator pendulum. The characteristic demanded of this alternator is that it shall begin to generate at a low speed, so that when the machine is started up the governor pendulum is brought into synchronism with the turbine before the latter has reached full speed. An alternator with a permanently

magnetised field system meets this requirement without the need for a separate source of excitation, or for slip rings. The rotor is a salient-pole assembly with poles cast from an aluminium-nickel-cobalt alloy, and the field winding consists of a few turns of wire per pole. The ends of the field circuit are brought out to terminals, so that the poles may be re-magnetised from the exciter of one of the sets, or from a battery supply should this be necessary. Alternatively, the alternator can be freed from the shaft, and by applying a three-phase supply to the stator, it can be re-magnetised by allowing it to run up to synchronism and thereby re-exciting it.

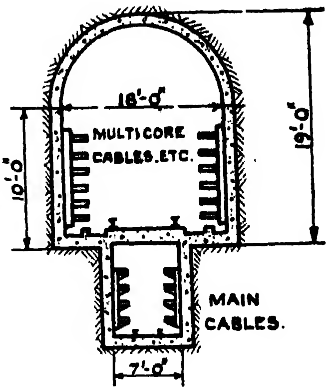

Fig. 607. Cable Tunnels.

Cabling and Connections. The cables from the alternators may be laid in trenches in the turbine house floor, or supported on racks in special tunnels which run from the main switchgear and control panels. Alternatively, fibre or stoneware ducts may be placed in the floor. In some installations, isolated phase construction is used for 5,000 amp. connections between the alternator and the step-up transformer. The connections consist of tubular copper enclosed in a circular copper housing, thus providing two walls of metal and three air spaces between conductors. Fig. 607 shows one form of cable tunnel construction.

Control Room. The switchgear and alternator control panels may be placed in a separate room, and arranged in linear, horse-shoe shaped or semi-circular formation. Some panels are of the desk type with the control and indicating equipment mounted on the front, and the protective relays and integrating instruments placed behind. A more detailed consideration of control rooms is given in Chapter XIV.

Electrical Protective Equipment. The protective equipment is generally similar in many respects to that used for steam power station plant.

Automatic overspeed and underspeed are fitted; also over-voltage and over-frequency relays are provided to take care of abnormal electrical conditions resulting from undue speed varia-

tions. Reverse power relays are included to disconnect the alternators should the gates or valves be inadvertently closed and the water supply to the turbines cut off.

Failure of insulation between turns can be detected by means of relays served by current transformers installed in the divided neutral leads brought out from each phase. A similar differential current relay in each combined neutral lead detects failure between phases. A voltage transformer connected between alternator neutral and earth, operates an alarm upon occurrence of a single line-to-earth fault. In the event of alternator trouble, the differential relays not only open the circuit involved, but can also be arranged to close the turbine gates to stop the set, and if desired, release CO_2 into the alternator housing. Some machines do not have any circuit-breakers or rheostats in the main alternator field circuits. A circuit-breaker is, however, provided to open the exciter field circuits automatically upon the operation of the alternator relays.

A water turbine behaves somewhat differently from a steam turbo-alternator when load is suddenly thrown off. The speed rise is quicker, and the rise of voltage is so rapid that the over-voltage relay will probably operate. This particularly applies to a system with a fair amount of charging kVA. This relay may be set to operate between 35 and 40 per cent. above normal voltage, but it can be adjusted to work between 60 and 140 per cent. of the normal voltage. It should be noted that it is possible for added reactance between alternators to reduce the synchronising stability under conditions where the load is subject to large and sudden fluctuations.

Voltage Regulation. High speed voltage regulators are usually employed. The problem of voltage control is made difficult by the governing characteristic of the turbine. If large electrical loads are switched off, the momentary rise of speed of the turbine influences not only the alternators, but also the exciters, and may result in a dangerous rise of voltage (Fig. 608). This refers to an alternator operating at a high power factor. The inherent regulation of standard machines (*i.e.*, the percentage rise above the rated voltage when full load is thrown off) is about 25 to 30 per cent. at 0·8 power factor, and 12 to 15 per cent. at unity power factor, assuming the speed and excitation to remain constant.

To overcome these voltage rises a scheme embodying a single non-repeating step (large loss of load is considered to be an isolated instance) of control in the main field has been used. By using a single non-repeating step, dangerous power swinging such as may

occur if fully regulated control of the main field was attempted, is eliminated. The scheme used on the State hydro-electric system in New Zealand, consists in switching into the alternator field circuit a resistance sufficient to limit the voltage rise to about 10 per cent. with the alternator on open circuit at about 30 per cent. above normal speed. The automatic voltage regulator then introduces its resistance into the exciter field circuit, and after a sufficient lapse of time for the exciter voltage to have fallen to a value corre-

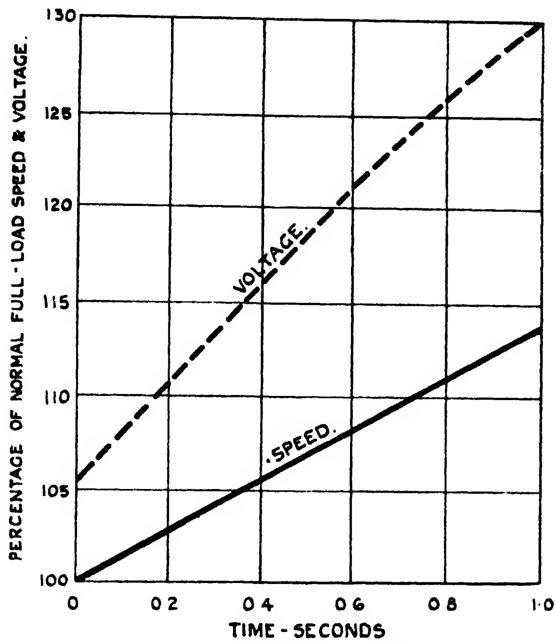

FIG. 608. Typical Curves showing Rise of Speed and Alternator Voltage on loss of full load, without Automatic Voltage Control.

sponding to about an open-circuit alternator voltage 10 per cent. above normal (say 2 seconds), the resistance in the main field is short-circuited. The emergency voltage control system then becomes inoperative until reset by hand or automatically.

Induction Alternator. Asynchronous alternators may be worth considering for isolated hydro-electric plants, to supply a large proportion of leading reactive power for line charging.

As a pure alternator, the use of the induction machine has been limited to small and usually unattended hydro-electric and wind-electric stations.

For hydro-electric use, the fact that the speed of the induction alternator varies between no-load and full-load is often of advantage in simplifying the control of the water turbine. The action of the induction motor is dependent on the existence of slip, conventionally termed positive slip. If the motor is driven by external means in the same direction above synchronous speed, the rotor e.m.f. reverses vectorily, and consequently, reverses the rotor current. The component of the stator current reflected back from the rotor is also reversed, and the machine thus becomes an alternator running with negative slip. The induction motor, when running, draws a magnetising current from the supply, which accounts for its lagging power factor, and even when driven at hypersynchronous speed as an alternator, this demand for magnetising current still obtains and the induction alternator must, therefore, draw lagging reactive kVA. from an external source in order that it may generate. This machine can only be used in conjunction with synchronous plant, the latter magnetising the asynchronous alternator and also "setting" the frequency at which the induction machine operates. Compensated induction alternators have been developed and are self-exciting. They can be operated independently of the electrical system and the power factor of the load generated can be adjusted by varying the position of the brushes on the commutator. Under all conditions, the synchronous alternators supply the magnetising current of the induction alternator; hence the use of the latter reduces the power factor of the system. Apart from this disadvantage, induction alternators can augment power on an existing A.C. system, by power derived from a windmill or water turbine. They do not require to be synchronised and can, therefore, be started and switched into circuit as and when wind or water power are available. The rotor speed can be varied to suit the requirements of a windmill or variable-head water turbine by varying the resistance of the rotor circuit. The frequency remains constant at the value set by the synchronous alternators on the system. There are limitations to the maximum capacity of induction alternators on a system, and 12 to 15 per cent. appears to be suitable for satisfactory operation.

Referring to Fig. 609 all the kWh. taken are recorded on the Trivector meter and the kWh. meter, and any units exported are given by the difference in the two meter readings. The Trivector meter is fitted with rachets to prevent both the kWh. and kVAh. sections reversing, and the reactive section of the meter will register

the wattless current of the induction alternators. The price paid for kWh.'s taken from the consumer should not exceed the running charge paid by the public supply authority, unless any firm kW. demand is supplied at the time of the authority's peak load. If a kWh. meter is only included, arrangements could be made to reverse the direction of this meter when an induction alternator is running, and so allow the consumer the benefit of any exported units. Power factor correction of the alternators is effected by a capacitor connected to the bus-bars. Each set is run up to about synchronous speed, by noting tachometer, and the circuit-breaker

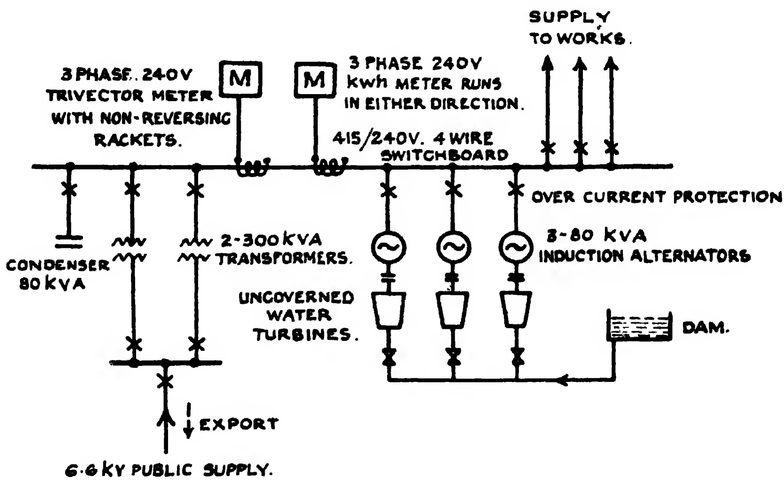

FIG. 609. Induction Alternator Power Plant.

is then closed, thus putting it in parallel with the incoming supply. The alternator pulls into synchronism with the supply and runs light until loaded by increasing the water supply to the turbine.

The alternators are standard three-phase machines with wound rotors, without slip-rings, the windings being permanently short-circuited. As already stated, they depend on the incoming supply for magnetising current; consequently they can only generate when operating in parallel with this supply.

PLANT OPERATION AND TESTING

It is generally assumed that the duties associated with hydro-electric power plants are of a routine character only, the day-to-day

operational instructions being prepared by the higher executive and passed on for attention. This is not quite the case in many plants, and such assumptions may lead to a restrictive outlook on the part of the operatives and tend to dull initiative. Admittedly, peak load operation results in unduly long periods when little or no plant may be in service, but a thorough knowledge of the plant and its functioning under both normal and abnormal conditions of operation is essential.

Generally speaking, no matter of a highly technical nature arises, save under emergency operating conditions, and due to housing accommodation in particular one of the engineers can usually be at hand at short notice.

The water turbines operate at much lower speeds than the corresponding steam turbines, and, in general, the electrical connections for the alternators, feeders and associated switchgear are simpler. Further, there are fewer auxiliaries, which all tend towards a corresponding reduction in duties and responsibility.

With certain exceptions, the simplicity of hydro-electric plant and its operation is evident. The use of coal demands a much higher degree of technical knowledge and experience than does the use of water. On the other hand, there is the irregular rainfall, and the problem of maintaining desirable levels in the reservoirs in both summer and winter seasons has to be considered, as their hour-to-hour determination requires careful judgment.

If the scheme includes smaller locks or head ponds, their operation will depend largely on the variable conditions of flow, and here again the hour-to-hour control will have to be ascertained by the station engineer. Instruments are provided for the purpose of level indication. The amount of water available varies with the weather, and the incidence of rainfall, and the control of this water requires that the station engineer and his staff should have full knowledge of the scheme and its relation to the system of which it forms part. It is sometimes thought that the water costs nothing, but it should be remembered that it can be converted into electrical units, which are equivalent to either coal, peat or oil units. The water made available is of value, and waste over dams, etc., should be eliminated as far as is economically practicable.

The forecasting of water conditions requires some care, and incorrect decisions may well result in considerable loss of revenue. The problem may also be further complicated if a number of stations

are dependent for supply of water discharged from a station at a higher level.

Water, especially at high pressure and momentum, requires careful control and a good working knowledge of the plant associated therewith. With plants designed principally for peak-load operation, the water available has to be arranged to suit a predetermined loading programme, particularly if the water storage is small, for heavy loss of water can take place in a short time. Average spillage figures usually vary from 5 to 10 per cent. The primary function of the hydro-station engineer is to utilise for power purposes as much as possible of the rainfall in the catchment area. The water levels of storage reservoirs should be high at the start of the dry season, but before the wet weather sets in, the reservoirs can be drained down if system conditions permit of this being done to create sufficient storage capacity. The formulation of a suitable operating programme is not always an easy matter, for varying sets of circumstances all have to be allowed for, and so much depends on the particular hydraulic and electrical system conditions of the scheme under review.

Hydro-stations usually have a higher installed plant capacity, which generally implies that there is less local switching, and also that they are shut down for extended periods. A water turbo-alternator could be run up and put on the busbars in about fifteen minutes, and 100 MW of plant could be put into service in approximately twenty minutes. In the event of it being necessary to run up a further machine, the operator need only turn the starting switch on the turbine control panel. Arrangements for automatic synchronising are also possible. A load-limiting device prevents overloading of a turbine.

The station engineer or superintendent is usually responsible for the following :—

Supervision of all station staff ; statistical records, *e.g.*, spillage, utilised and compensated water, units generated and sent out, meteorological data, cost data ; allocation of inspection, maintenance and testing work, *e.g.*, turbines, alternators, exciters, switchgear, surge towers, draught tubes, pipe-lines, gates, screening plant, air pressure vessels, air and oil coolers, etc.

The shift charge engineer is responsible for the general operation and running maintenance of the plant, including voltage and load control. The training of a shift engineer for steam power stations takes some years, whereas for hydro-stations, men of reasonable

electrical and mechanical aptitude having little or no operating experience or special technical training, have been trained to a satisfactory standard in a comparatively shorter period.

A control room engineer, if employed, will normally carry out the switching, record meter readings and generally assist with the compilation of operating statistics.

A turbine driver and an auxiliary plant attendant will also be required for each shift.

Running maintenance work will generally be carried out, according to need, at monthly, quarterly, and yearly periods, *e.g.* :—

Monthly.	Centrifuge guide and thrust bearing oil.
	Greasing and cleaning of valves.
Quarterly.	Examination and cleaning of voltage regulators and control panel equipment.
	Testing of governor relief valves.
	I.R. tests of all motors.
Yearly.	Renew oil in certain bearings and valves, etc.

The following is typical of the electrical plant but is extended to include all sections of plant.

Item.	Monthly Check	Annual Overhaul.	Major Overhaul every 5 years.
Stator . .	Nil.	Cleaned and inspected. I.R. test.	Thorough examination of all parts. Cleaning, etc. as required.
Rotor . .	I.R. test.	Cleaned and inspected in position. I.R. test.	Removed. Thorough examination, Cleaning, etc. as required.
Brush gear .	Cleaned. Brushes replaced as required.	Cleaned and inspected. Brushes renewed.	Cleaned and necessary adjustments made.
Slip-rings .	Cleaned. Polarity reversed if required.	Cleaned. Turned down as required.	Cleaned and turned down or replaced if necessary.

Water Control. A complete control panel may be installed which shows the general layout of the water-flow system, and upon which are mounted indicating instruments in diagrammatically correct positions. From these instruments the amount of each water-gate opening, and the rate of flow into the main channel or other sections, can be seen. The rate of flow of compensation

water can also be indicated. Control switches below each gate-position indicator can serve for the remote control of the gates, and in this way the rate of water flow may be varied to suit the operating conditions. Under certain extreme water conditions, the operation of the gates may have to be carried out with care, and automatic arrangements can be included to take care of all conditions. Water-level recorders are provided to indicate the prevailing levels at the dam, surge tower, tail-race, and other points of the system. The level is usually given by an electrical resistance element immersed in the water, and the reading transmitted by cable or overhead line to the control room. In one scheme records are kept of the amount of water spilled over the dams, and the control by main and subsidiary reservoirs is such that if all the spilled water could be turned into power at the stations, the production on the average would be increased by less than 5 per cent. An incidental effect of the reservoir control is the marked mitigation of flooding in the lower reaches of the river.

Supervisory Control. The system uses the same channel for transmission as the main carrier-current communication, and supervisory operations may take place while speech is in progress.

With such a system of control, circuit-breakers can be closed or opened, and the current and voltage of each circuit indicated. Plant operation is also possible, and has been employed on a number of stations. This equipment provides for fully automatic starting up and shutting down from a remote control station, and local starting up and shutting down from the power station itself.

Audible and visible indications of all operating sequences are given at the remote control station.

A mimic diagram is provided on the supervisory control panel, on which the indicating instruments and operating switches are also mounted.

Plant Operation. The manufacturer's instructions should be followed, and in practice it will be found that operational procedure will vary somewhat in detail, but the general principles are the same. In starting any turbine, it is essential to ensure that the oil system is functioning correctly. The guide vanes of a reaction turbine or the needle valve of a Pelton wheel are opened to admit water for running up the set to normal speed, and the governor is brought into service. The alternator field switch is closed and the incoming machine voltmeter connected, after which the voltage is gradually increased to equal that of the busbars should they already be

energised. The synchroscope is connected in circuit and the direction of rotation noted—fast or slow—relative to the busbars. The turbine speed can be adjusted by operation of the governor control motor from the control panel. The alternator circuit-breaker is closed just prior to the synchroscope reaching its vertical position, so that the breaker contacts will make circuit when the pointer is on twelve o'clock. After synchronising, the 'scope and incoming voltmeter are switched out of circuit. On increasing excitation the alternator voltage is raised and the set is made to carry a larger share of the wattless current. This lowers the power factor and improves that of the other sets on the busbars. The set is made to take up more load (kW. or useful load) by adjusting the governor so as to admit more water. Simultaneously the excitation is increased to maintain the voltage and make the alternator operate at a power factor consistent with that of the electrical system. When shutting down a set, the load is lowered by adjusting the governor control to reduce the amount of water flowing through the turbine. The excitation is gradually reduced until the ammeter shows no current, when the main circuit-breaker can be opened. The exciter field switch is opened and the set shut down.

Switching Operations. Special care is required in carrying out switching on higher voltage equipment, and the safety regulations and permit-to-work instructions should always be followed.

When an overhead line, transformer, busbar system, circuit-breaker or any other higher voltage equipment is commissioned or returned to service after repair, it is desirable to test before connecting it to the system. Voltage testing is usually provided for this purpose, but a spare alternator can be used if one is available, and if a duplicate or sectionalised busbar is included. The alternator should be of sufficient capacity to supply the magnetising current of the line to be tested. The alternator neutral should be connected to earth (or the neutral of the step-up transformer) so that an earth fault will show itself. The alternator field switch should be open, and the rheostat placed in the minimum volts position. The set is then run up to normal speed, and the alternator and overhead line circuit-breakers are closed. The incoming voltmeter is connected, the field switch is closed, and the excitation is gradually increased until normal voltage obtains. If the line is in order, full voltage can be applied. An earth fault on the line, say, on the blue phase, will show a heavy unbalanced current on the corresponding ammeter as the alternator excitation is increased, and it

will not be possible to maintain normal volts. Further information concerning switching operations, will be found under Switchgear, Chapter XIV, also in the author's book, " Sub-station Practice."

Automatic Plants. It is essential that the various parts should be very robust and safe, and that the relay-controlled contacts should be perfect. Normal operation consists of three main functions :—automatic starting of the machines, their voltage regulation, and supervision of their normal operation. Experience shows that bearing cooling deserves special consideration, especially where the cooling system is supplied direct from the high pressure pipes. The orifices of the valves, being very small, are liable to choke very quickly even when strainers are included. In manually-operated stations such choking causes but little interference, since the operating personnel can clear any obstruction. Remote water-level control is generally satisfactory, but where connection between reservoir and station is by overhead line, the operating devices may be affected if they are sensitive to lightning surges.

A most important feature in both semi- and fully-automatic plants is the degree of simplicity. All refinements are likely to introduce new risks, and may ultimately prove to be more trouble-some than the risks they were intended to eliminate.

The designers, and operating personnel, of these plants, should be encouraged to analyse the experiences obtained from various plants, in an endeavour to eliminate all unnecessary refinements which may tend to impair reliability.

Hydro-stations can be started and stopped by short wave radio, and in some cases where the main antenna is optically hidden from the control point this can be reached by reflection from a peak in the vicinity.

Staffing. The staffing generally varies according to the plant capacity, but is not very large. For a 30 MW station, there may be three men on each shift, and the usual staffing will include :—station superintendent, four shift charge engineers, four turbine drivers, four auxiliary plant attendants, fitter, electrician, reservoir attendant, and a number of general manual workers.

The North of Scotland Hydro-Board have a technical staff training college, the idea being that all technical staff will, on appointment, spend a short training period in the college before they are allocated to specific duties, returning for further instruction and refresher courses when necessary. Instruction is of a practical nature, including operational duties at hydro-electric, Diesel and

steam stations, maintenance work on transmission and distribution systems, together with visits to projects under construction, also to manufacturers' works. Lectures are given on the schemes, the economic and communal life of the Highlands, and on future planning. In this way, staff recruits are able to take up their duties with a knowledge of the programme, and with a better understanding of their position in relation to other interests in the Highlands.

Turbine Tests. These may be divided into two principal groups, namely :—(1) governor tests, and (2) efficiency tests.

(1) Governor tests are carried out to determine the variations in speed and water pressure which occur when various electrical loads up to full load are suddenly removed from the machine.

Tests are also made to determine the ability of the turbine to pick up load rapidly, and to ascertain that there is no hunting or, in other words, that the governor is stable.

To carry out governor tests, it is necessary to provide means for loading the turbine, and this is rather difficult for very large machines. One method is to dip plates in the tail-race, and an alternative is to make use of a water resistance in the form of a portable tank or a permanent test pond. Using the tail-race may cause difficulties with fish, and there may be insufficient depth of water. Small machines connected to a large supply system can be loaded up and have the loads thrown off without any undue electrical disturbances. Typical tests for steam plants are given in Chapter IX, Vol. I. With a test pond, the load is adjusted by varying the immersed area of the electrodes, and a considerable quantity of water is required to carry off the heat produced by a fully-loaded large machine. The water required to carry off P kilowatts for a temperature rise of T °F is $= \frac{6{\cdot}8\ .\ P}{T}$ gallons per minute. For a 12 MW machine at full load and a rise in water temperature of 10° F., the quantity of water required will be $= \frac{6{\cdot}8\ .\ 12{,}000}{10} =$ 8,160 gallons per minute.

In one station, large liquid loading resistances are used for the periodic testing and adjustment of governor settings of 50 MW machines. The resistances carry the full load current of 1,920 amps. at 15 kV. One resistance tank is provided for each of the three phases, and concentric electrodes are arranged to vary the immersed area. The water is drawn from the pipe-line and returned to the tail-race with a temperature rise of about 86° F. at full load. A

tachograph is useful for speed and water pressure measurements, as reliance is not placed on spot readings of pressure gauges and tachometers. The instrument is driven off the governor pendulum shaft and carries pens for recording speed, Servo-motor stroke, and pressure in the turbine casing.

(2) Efficiency tests are taken to ensure that a new machine complies with the specification and contract guarantees, and can also be useful to ascertain the performance of plant which has been in service for some time.

In testing a turbine on site, the speed and head are kept as close to the designed values as operating conditions permit; but tests for the efficiency of a model are far more extensive.

Actually the larger turbine will have higher efficiencies than the model because of the scale effect, and certain known corrections are applied to take this into account. The efficiency $= \dfrac{\text{output}}{\text{input}} =$
$\dfrac{\text{output}}{\text{output} + \text{losses}} = \dfrac{\text{useful work done}}{\text{energy supplied}}.$

To ascertain the efficiency of a turbine, the output is measured from the integrating kWh. meter of the alternator, and from a knowledge of its efficiency which has been determined on the test bed in the maker's works. The energy input to the turbine can be ascertained by measuring the water supplied to it and the net head under which it operates. Various methods are available for measuring the quantity of water supplied to the turbine, and two are outlined.

Pitometer Test

This can be used where there is a long straight pipe so that the water is free from eddies. The pitometer has two parallel tubes encased in a rod which passes through a valve into the pipe-line at right angles to the centre line. There is a small orifice at the end of each tube, which is connected to a manometer outside the pipe. The orifices are close together; one points upstream to receive impact pressure; the other points down-stream and is under the normal pressure obtaining at the orifice position. The velocity of the water sets up a difference of pressure across the orifices and the liquid in the manometer is thus displaced. The velocity at this position can be calculated from the displacement.

Before or after the tests, two diameters at right angles are explored to ascertain the distribution of velocity in the pipe-line;

and from that, the pipe co-efficient, or ratio of mean to central velocity, is determined. During the tests, the orifices are kept at the centre line of the pipe. The rate of flow is the product of the central velocity, the pipe-co-efficient and the cross-sectional area of the pipe, or Q (cusecs) $= V \cdot Kp \cdot A$. Where $V =$ central velocity in feet per second, $Kp =$ pipe co-efficient, and $A =$ sectional area of pipe, square feet.

Salt Velocity Test

This method was devised by Professor Allen of the Worcester Polytechnic Institute, U.S.A., and is simple and reliable. The principle on which it is based is that the electrical conductivity of water is increased by introducing salt. At the upper end of the pipe-line or aqueduct, a salt solution contained in a tank is injected through a number of spring-loaded valves which are disposed over the section of the pipe to ensure a uniform distribution of the solution. Some distance down-stream a circuit, including a recording ammeter, is connected across an arrangement of electrodes. The electrodes are connected to an A.C. supply of 110 volts, and provision is made in the circuit to record time, opening and closing of the quick-acting valve on the tank, and the electrode current, on a moving chart. Two pairs of electrodes connected in parallel may be fixed in the pipe on diameters at right angles to each other, and spaced about 3 ft. apart. Each pair of electrodes is built up of two flat steel bars which are insulated from each other and from the wall of the pipe, and the gap between them increases towards the centre of the pipe. When the solution reaches the electrodes it lowers the resistance of the circuit, and indication of this change of condition is given on the ammeter. Injections are repeated during the test. The time between the injection of the solution and the centre of gravity of the ammeter deflection is measured on the chart. The volume of the pipe-line between the point of injection and the electrodes is known from actual measurements. The rate of flow in cusecs. is this volume divided by the time, as measured on the chart.

Measuring Weir. Some idea of the plant performance may also be obtained by installing a measuring weir in the tail-race, any lowering of efficiency due to wear or leakage being detected. In two plants of large size in which turbine gate leakage was measured, this amounted to less than 0·3 per cent. of full gate discharge in the one case, and less than 0·1 per cent. in the other case

Formerly, a turbine gate leakage of 1 per cent. was not considered excessive.

Venturi Tube. In some plants a venturi tube is placed in each pipe before entry to the turbine house to measure the water flow.

COSTS

The interconnection of steam and hydro-electric plants will promote the best economic results in certain cases by utilising to the greatest advantage the available water flow, especially if possibilities for storage are absent or deficient.

The factors involved in the economic evaluation of hydro-electric development on an interconnected steam-and-hydro-electric system are rather complex, and it is essential that each scheme should be considered on its merits. Unfortunately, in many schemes, the complexities and technicalities involved tend to grow as the schemes develop. Where the proportion of hydro-power to steam-power is large, it is necessary to maintain a reasonable balance between the two plants installed on the system to meet deficiencies in output at the hydro-stations during drought periods. On the other hand, the hydro-plants may be competing with each other to a greater or less extent for space on the system load curve in wet weather. It is impossible to give any figure for the cost of hydro-electric power or for the limiting cost at which such developments may become economically justifiable. This depends essentially on the cost of development and operation of any competing power, and on the purpose for which the energy produced is to be utilised.

Generally speaking, the smaller the quantity of water, the higher is the cost per kW. and per unit distance the water has to be conveyed to the power station by pipes or other means. The cost per kW for generating and ancillary plant also increases as the quantity falls, and it may be stated that the cost per kW. of transmitting electrical energy unit distance also increases as the quantity falls. The cost of storage does not follow any general rule, as it is largely dependent on topographical and geological features, but in general, the tendency is for the storage to be cheaper per kWh. stored in a large scheme.

The main component in the cost of hydro-electric plants is the interest and depreciation (or sinking fund) charges on the total capital cost. The rate of interest, and the provisions for depreciation or sinking fund are of particular importance in the economy

of such schemes. The interest charges on the initial capital expenditure, together with other fixed charges such as insurance, rates, taxes, and sinking fund, usually form from 60 to 70 per cent. of the total cost of power, and are independent of output. The other charges—administration, labour, stores, repairs, etc.—vary somewhat with the output, but not nearly so much as in fuel-operated power plants. The capital costs will also include: preliminary investigations; their promotion and organisation; land and water rights, and rights of way for transmission lines, etc.; all constructional work and engineering charges associated therewith in respect of fees, salaries and wages, and interest on capital expended up to the commissioning of the plant.

The cost of fuel is by far the largest item in the annual cost of production of energy at a steam power plant. Where the fuel cost—coal, peat or oil—is very high, the balance swings in favour of greater hydro-electric development. The minimum steam plant installation on a system should be such as to ensure a reasonable degree of security of supply in the event of periods of drought, which appear to occur in cycles, *e.g.*, every 5, 7, 10 or 15 years. On some systems one of the principal functions of a steam plant may be to take over the base load at times of low inflow at the hydro-plants, and this influences the operation and the programming of maintenance as compared with the usual practice on an all-steam system.

The economic development of hydro-plants depends essentially on :—

(1) Whether there exists, or is likely to exist, a market for the power.

(2) Whether the price at which the power can profitably be sold is, firstly, such as industrial, commercial and domestic consumers can afford to pay and, secondly, less or at least not greater than the price of power from a fuel-operated station.

The value of any electric power supply may be divided into two parts: (1) energy or kWh. value; (2) capacity or kW. value.

The majority of water power schemes involve a large capital expenditure, as the development must be where it is found, and in many cases long higher voltage transmission lines are necessary. The capital cost depends on many factors: topography and geology which affect civil engineering works; value of water rights and amenities or other interests affected; availability of local labour; housing and welfare of employees. The factors involved vary for each site, and no real comparison can be made.

The constructional costs are, in general, divided between civil works and plant in the proportions of: 74 per cent. civil, 26 per cent. plant.

The working costs per kW. of plant installed show a steady fall as the size of the scheme increases above 5 MW, while for smaller plants the cost increases rapidly. The large extent to which interest on capital and charges for depreciation enter into the total working costs is shown in Fig. 610.

The total cost of construction is invariably higher than that of steam or oil plants of similar capacity, and the annual capital

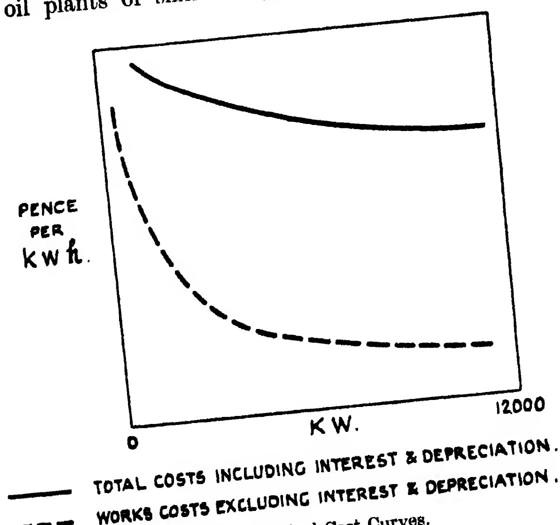

Fig. 610. Typical Cost Curves.

charges for interest and depreciation are, therefore, correspondingly higher. On the other hand, running costs are comparatively low and do not depend to any extent on the loading, and may generally be regarded as a fixed charge per annum. As already mentioned, the capital expenditure depends on many factors and varies with each scheme.

On a pipe-line scheme, low cost of development will be made possible with high head and small water flow, and good storage facilities which serve a number of plants; a favourable dam site having good foundations in a narrow valley with a minimum of material in the dam construction; good pipe-line route affording straight line with moderate gradient for a greater portion of the

distance, and then a steep fall to the turbine house ; a small number of large machines ; short transmission lines, and as high a load factor as possible.

With a river or canal scheme, high cost of development is usually inevitable if the following are encountered :—relatively low head and large water flow ; unfavourable dam site with wide valley, and excessive dam materials required ; a large number of small capacity machines ; unduly long transmission lines, and low load factor.

Regarding load factor, there is a contrast between water and steam or oil, as every unit sent out from a steam or oil station costs a definite amount in fuel. Thus, there is a limit to the charge per kWh. below which energy sold would result in a loss. With water power, such a condition does not obtain, except when the energy produced can be sold without any difficulty due to the limitation of water. Generally speaking, the working costs would not be affected by the production and sale of additional units, providing extra plant is not required, and the transmission and distribution systems are such that no further charges would be incurred.

The total costs per kWh. of output of a hydro-plant vary almost inversely as the output, and a market for full capacity is of great importance. If the load factor is high, the capital cost will be spread over a large number of units, and the cost per kWh. will be lower. In a station designed to supply peak load units, a low load factor development may in certain instances be justified economically.

Although the capital costs are up some 400 per cent. above the pre-war level (1939), there is still approximately a margin of from 15 to 18 per cent. in favour of hydro-electric as compared with steam-electric plants.

The comparative costs of the various sections of works, etc., associated with hydro-plants are broadly as follows :—

	Per cent.
Dams and equipment, etc.	10
Power plant and equipment	22
Hydraulic installation	20
Electrical installation	26
Flooding drainage	1
Engineering and inspection	5
Interest during construction	6
Contingencies	10
Total	100 per cent.

Reservoirs, dams and waterways are said to constitute about 60 per cent. of the average capital cost for American hydro-plants of 50 MW with heads up to 500 ft.

Plant costs for four stations constructed and put into operation between 1933 and 1936 are given in Table 99.

TABLE 99. *Station Plant Costs*

Station	1	2	3	4
Average net head . . ft.	106	380	66	150
Speed . . . r.p.m.	214·3	428·6	214·3	250
Capacity of each set . . MW	11	12	6	10·5
Total plant installed . . MW	33 (1—250 k House s	12 (2—500 kW. House sets)	24	21
Cost per kW. installed . . £	4·2	2·9	5·5	4·0

These include cranes and main stop valves.

One scheme consisting of five stations, the largest single machine being 12 MW, having a total installed capacity of 102 MW with three house sets (2--500 kW. and 1—250 kW.) cost about £30 per kW., including transmission lines, in 1933–1936. The data for this scheme for the year ended December, 1947, were as follows :—

Total units generated = 203·5 millions.
Peak load on system = 107·1 MW.

REVENUE ACCOUNT

Expenditure

(*a*) Generation costs (including maintenance) . . £45,940

$$\text{Cost per unit generated} = \frac{45{,}940 \;.\; 240}{203{\cdot}5 \;.\; 10^6}$$
$$= 0{\cdot}054 \text{ pence.}$$

(*b*) Management and general (including insurances, legal, etc.) £17,394

$$\text{Cost per unit generated} = \frac{17{,}394 \;.\; 240}{203{\cdot}5 \;.\; 10^6}$$
$$= 0{\cdot}026 \text{ pence.}$$

(*c*) Rates and taxes £16,051

$$\text{Cost per unit generated} = \frac{16{,}051 \,.\, 240}{203{\cdot}5 \,.\, 10^6}$$
$$= \underline{0{\cdot}019 \text{ pence.}}$$

(*d*) Debenture interest £119,194

$$\text{Cost per unit generated} = \frac{119{,}194 \,.\, 240}{203{\cdot}5 \,.\, 10^6}$$
$$= \underline{0{\cdot}14 \text{ pence.}}$$

(*e*) Debenture redemption £18,556

$$\text{Cost per unit generated} = \frac{18{,}556 \,.\, 240}{203{\cdot}5 \,.\, 10^6}$$
$$= \underline{0{\cdot}022 \text{ pence.}}$$

Total cost per unit generated = $\underline{0{\cdot}261 \text{ pence.}}$

(*f*) Dividends on Ordinary Shares £36,750

(*g*) Balance carried forward £4,842

Total (*a*) to (*g*) = £258,727 Expenditure.

Income

	£
From Sale of Energy	245,565
Rents Receivable	1,133
Other Receipts	3,515
Balance last account	8,514
Total	£258,727

CAPITAL ACCOUNT

	£
Share Capital	245,000
Loan Capital Outstanding :—	
5 per cent. Debentures . . .	1,326,964
4 per cent. Debentures . . .	1,306,437
Investments (at cost)	131,088
Reserve	125,961

The total capital expenditure for this scheme, including certain transmission lines, was £3,131,700, so that the cost per kW. of installed plant is approximately £30, as already stated.

The annual load factor of the stations (combined)

$$= \frac{203{\cdot}5 \,.\, 10^6 \,.\, 100}{103{,}250 \,.\, 8{,}760} = 22{\cdot}5 \text{ per cent.}$$

TABLE 100. *Annual Charges as Percentage of Capital Cost*

Section of Works	Life Years	Annual Charges as Percentage of Capital Cost		
		Repairs and Maintenance	Renewals	Total
Dams, channels, etc. . . .	60	0·50	0·55	1·05
Buildings	50	0·75	0·80	1·55
Pipe-lines and steelwork . .	30	1·00	2·00	3·00
Sluice gates, screens, etc. . .	30	1·50	2·00	3·50
Turbines, alternators, switchgear and transformers . . .	30	3·00	2·00	5·00
Transmission lines . . .	25	0·75	2·60	3·35

The average cost of low and medium head hydro-electric schemes in 1949 varied between £60–£80 per kW of installed plant with a running cost per unit generated approaching 0·25 pence.

Typical hydro-electric costs for 1953 were : overall cost per unit (kWh) generated 0·517d., interest and redemption charges 0·479d. ; leaving operation and maintenance costs at 0·038d.

The approximate annual charges for repairs, maintenance and renewals as percentages of the capital cost of the various sections of the works associated with a hydro-electric plant are given in Table 100.

TIDAL POWER

Tidal power is by no means a recent innovation, for tide mills existed in the early centuries. A reservoir is formed by building a dam across a tidal creek, and the incoming tide is admitted by automatic sluices or flap valves, which close to prevent the water flowing off when the tide falls. The water in the reservoir is then used to drive the mill as the tide goes out.

The utilisation of tidal power on a very large scale resolves itself into an economic question in relation to other available or potential power supplies in the area under review.

The cost of tidal power developments is closely linked with the topographical difficulties which have to be surmounted. The cost of civil engineering works is considerable on account of, and difficulty in finding satisfactory foundations for, the embankment and cut-off dams. For this reason such developments are only considered at certain sites, *e.g.*, the Severn, where the topographical features and other conditions in respect of foundations, the tidal flow and the geographical position generally, favours the production of a large block of electrical energy at the lowest possible cost per unit. It would appear that the economic margin in favour of tidal power developments is relatively small, and while in the interests of conservation of coal resources such developments should be encouraged, it is difficult to say just when would be the ideal time to embark on the construction of such schemes involving large expenditure of capital.

The technical difficulties that have existed under the onerous conditions of widely fluctuating head of water, have now been overcome by the Kaplan or other types of propeller turbines. The power that can be produced depends on the range of the tide, and this varies considerably from place to place. The approximate average range at spring tide is 16·5 ft., and 8·5 ft. at neap tide round the coast of Britain. At certain places on the Severn the average spring tide is about 42 ft. The range of the tidal varies gradually, and it is greatest at new moon. At this period the gravitational forces of the moon and sun combine, and spring tidals are produced. Spring tides also appear at full moon. When the moon is in the first and last quarters, the sun and moon act at an angle to each other, so there will be neap tides. The range also varies with the seasons of the year. During the equinoxes of March and September, the moon is nearest to the earth ; therefore the highest spring tides occur. In June and December the moon is farther from the earth, so that in these months the lowest neap tides would be recorded. The spring range is about twice that of the neap range, which means that approximately four times more power can be produced on a spring tide than a neap one, because increase of head also increases the water available.

If turbines are installed of sufficient capacity to utilise the energy of a spring tide, they will be only partly loaded on neap tides. The load factor will, therefore, be low, and the cost high. If smaller turbines are employed, some energy will be wasted on the spring tides.

Tidal power is independent of climatic conditions which affect

hydro-electric stations, but the frequency and effect of storms, including unfavourable wind and tide conditions, may affect the reliability of the station output. If tidal power were to become an economic possibility, it has been suggested that efforts should be directed towards :—

(*a*) Reducing the cost of plant and machinery by improving and simplifying design.

(*b*) Reducing the cost and extent of the transmission system.

(*c*) Improving the low-head efficiency of turbines operating over a wide range of head.

(*d*) Developing simple and cheap gas-turbines or pumped-storage plants designed for system requirements rather than as an adjunct to the tidal power station.

When load is thrown off a tidal station under fault conditions, a standing wave may be set up in the upstream and downstream channels, which may affect navigation.

The only practical method of using tidal power is the impounding of the tidal water in a basin, and utilising the head created by the difference between the level in this basin and that of the falling tide. The converse is also possible : using the water of the rising tide to fill a basin, previously emptied on the falling tide. The basin method and various adaptations of it form the basis of all recent proposals in connection with tidal power schemes.

The conditions favourable for the development of tidal power in any country having suitable sites are :—

(1) A large electrical demand, and an interconnected or grid electrical system.

(2) A shortage and/or a high price of fuel.

(3) The absence of extensive undeveloped cheap water power.

Tidal Phenomena. The tides result from the combined attraction of the sun and moon on the water of the earth's surface, and the relative daily and periodic motion of the three bodies. The tidal range depends on :—

(1) Relative position of the three bodies, with the influence of the moon predominating.

(2) Depth of water and configuration of the estuary.

The resultant effects are :—

(*a*) Two tides occur daily.

(*b*) Interval between successive high tides is twelve hours twenty-four minutes.

(*c*) 706 tides per annum.

(*d*) High tides occur fifty minutes later each day.
(*e*) Tidal cycle occupies about fourteen days.
(*f*) Tidal range increases steadily from neap to spring tides over the half tidal cycle.
(*g*) Tidal range increases upstream until the river is reached, and then decreases.
(*h*) Period of the ebb tide exceeds that of the flood.

The daily output from such a power station varies, but the energy available, monthly and annually, is almost constant. An insurmountable drawback with all such schemes is the comparatively low working head, and, consequently, the large quantities of water to be handled; also the intermittent or variable output, depending on whether it is a single-basin or a two-basin scheme.

Single-Basin Scheme. This is the principal method of utilising the tides for electric power development, and employs a single basin

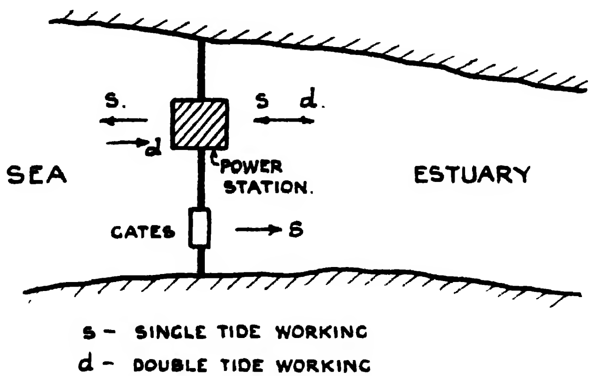

FIG. 611. Single Basin Tidal Scheme.

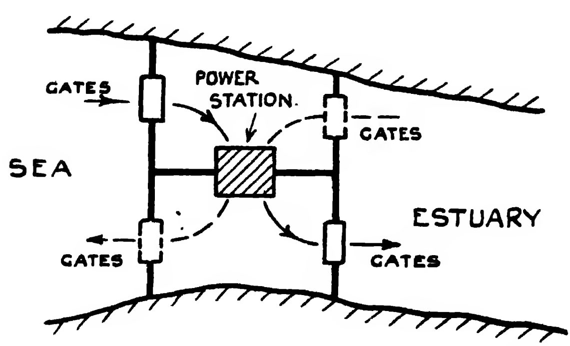

FIG. 612. Alternative Scheme, Double Tide Working.

formed by the construction of a barrage equipped with gates across an estuary.

The assumptions made in considering the principles of operation are :—

(1) Uniform tides, with equal periods of flood and ebb.

(2) Constant basin area at any level.

(3) Constant plant efficiency.

(4) Negligible head loss.

These will, however, have to be considered when making practical calculations of tidal output.

Figs. 611 and 612 show the layout for a single basin scheme.

Multiple-Basin Scheme. A multiple-basin project may provide a continuous output of power and energy. The following limitations,

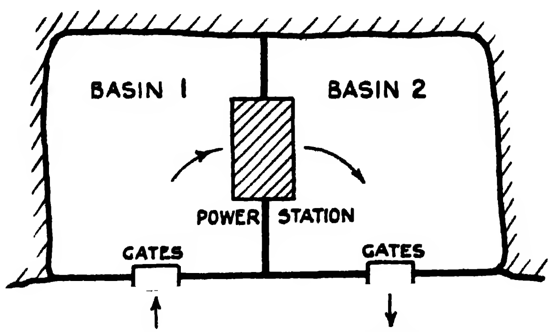

FIG. 613. Two-basin Tidal Scheme.

which apply to the simple scheme (Fig. 613), are to some extent general for multiple-basin schemes :—

(1) Operation may be complicated to some extent.

(2) The effects of the assumptions made under the single-basin scheme are unfavourable.

(3) Output between spring and neap tides is not equalised ; the steam plant replacement value is therefore limited.

(4) The best results are obtained when the two basins are of equal area.

(5) The normal tidal régime is disturbed

(6) Expensive and difficult to adapt to local conditions.

General.

The only scheme contemplated in this country is that of the Severn Barrage, which it is estimated will have a plant capacity

of 800 MW, will cost some fifty million pounds, and take eight years to construct. The cost per unit generated was 0·2*d*. on a 1945 basis. It is only in exceptionally favourable circumstances that pumped-storage can economically come to the assistance of tidal power. Should the contemplated Severn Barrage Scheme be constructed, it will not reduce by a single kW. the generating plant capacity provided elsewhere to meet the peak demand. It has been suggested that this scheme should be reserved for a time of trade depression, when labour and materials are readily available at reasonable cost.

The average efficiency of thermal power stations is tending to rise, and ultimately, with more reheat stations, figures approaching 40 per cent. are possible. The tidal schemes will, therefore, have to be compared with the coal saving effected not only on present-day plant efficiencies, but also on future efficiencies.

It has been suggested that, if it is deemed necessary, one way of giving the Severn Barrage firm kilowatts would be to use gas turbines. This could be done in two ways : (1) by providing separate stations ; and (2) providing these on the barrage, coupled through clutches and triple reduction gearing to the alternators when there was no tidal water available for driving the turbines. It is doubtful if mechanical and hydraulic considerations would permit of the second method being used.

Pumped Storage

The introduction of the pump-turbine permits pumping of water into a storage reservoir during off-peak periods and using the elevated water to drive the turbine during periods of large-energy demand. This reversible hydraulic machine is capable of operating at high efficiency as either a turbine or a motor driven pump.

CHAPTER XXV

DIESEL-ELECTRIC PLANTS

Diesel-electric power plants have been chiefly used as central stations for small supply authorities and works, and also to supplement hydro-electric plants where stand-by generating plant was deemed to be necessary. They have also been used as house service sets in large steam-electric power plants.

Up till about the year 1920, the most economical prime mover for the smaller power plants was the gas engine. Subsequently, the compression-ignition oil engine was favoured where suitable fuel oil was available at an economic price.

In many places transport was either not available or too costly for oil to be transported, but in spite of these difficulties, many of the earlier engines were designed to operate on either gas or oil, in the latter case as compression-ignition engines. Such engines were primarily designed as oil engines, but provision was made for removing the atomiser and substituting a sparking plug, together with a magneto. Arrangements were also made to increase the clearance volume or combustion space, and lowering the compression ratio from 12 : 1 to 6 : 1 when the engines were required to run on gas.

The reasons for the development of Diesel-electric plants in many countries are the increased demand for electric power since the war, and the difficulties experienced in the reconstruction and enlargement of hydro-electric plants. In some cases, station capacities vary from 1 MW to 36 MW, but stations of 50 MW capacity employing two 25 MW sets have been built. One plant consists of 15 MW sets running at 115 r.p.m., eight cylinders, double-acting, two-cycle, solid injection, with cylinders of 33 in. bore and stroke 59 in.

It is of interest to note that the British Electricity Authority have placed orders for Diesel plant to be installed in peak load stations. The largest station when completed will have five 2 MW sets.

The following are reputed to be some of the largest plants in operation at the present time :—

Horse-power	
23,000	Europe.
51,200	Shanghai.
51,900	Mexico (44,100 H.P. at 7,500 ft. above sea-level).
64,800	America (gas-Diesel engines—18 sets).
216.000	America (natural gas-spark ignition—138,000 kW. total).

The oil engine has advantages which make it very suitable for small and medium output power plants, some of which are :—

(1) High operating efficiency which bears no relation to output.

(2) No stand-by or banking losses.

(3) Limited cooling water supplies suffice.

(4) Quick starting and quick load pick-up is possible.

(5) Simple plant layout.

(6) Reduced space and cost of buildings.

(7) Easier handling of fuel, smaller storage space for fuel, and no refuse to dispose of.

The disadvantages are :—

(1) Fuel may have to be obtained from abroad.

(2) Comparatively high plant cost per kW.

(3) Plant floor area and costs increase in proportion to increase of capacity and generally fix economical limit at about 15 MW.

Diesel-electric plants can be classified as : manual (attended) plants ; and automatic plants. The latter are used for installations which are intended to serve as stand-by to large steam turbine plants or hydro-electric plants, having to be started up immediately on failure of supply.

PLANT LAYOUT

The engine layouts are similar in many respects to those obtaining with steam turbo-alternators, and the accompanying illustrations show typical installations. Fig. 614 shows a single-unit station having an 8,000 B.H.P., 187·5 r.p.m., two-stroke, double-acting engine. It has eight cylinders, 25·5 in. bore, 34 in. stroke. The alternator output is 7·5 MVA. (5·7 MW) and it is a 32-pole machine operating at 6·3 kV., 50 cycles per second, open type design, with main and auxiliary exciters. A welded steel bedplate is provided, and the pistons are oil-cooled, with water-cooled cylinders, heads and atomisers.

Figs. 615 and 616 illustrate the layout of six 12-cylinder, 29-in. bore, 40-in. stroke, two-cycle, mechanical injection engines, running at a speed of 167 r.p.m. The sea-level rating is 8,650 H.P. The station is placed some 7,500 ft. above sea-level, and the corresponding full-load rating is about 6,680 H.P. The output of the engines can be increased by some 10 per cent. to 7,350 H.P. by using the centrifugal scavenging blowers to slightly supercharge the engines. The plant is operated as a base-load station on a system having hydro-plants approaching a total installed capacity of 400 MW. Heavy fuel oil is used, bunker-C class, but provision is made to use natural gas at some future date. Air blowers, each rated at 45,000 cu. ft. per minute, 3·6 p.s.i. pressure, supply each engine with scavenging air. Each blower is driven by a 1,000 H.P. squirrel-cage, delta connected motor, which is connected across the alternator terminals. During starting, the blower is brought up to speed with the alternator by energising the main exciter field from a battery. A separate motor-driven exciter could also be used for this purpose. Thermal over-current relays operate an alarm, and induction overcurrent relays trip the alternator and field circuit-breakers in the event of heavy sustained overload.

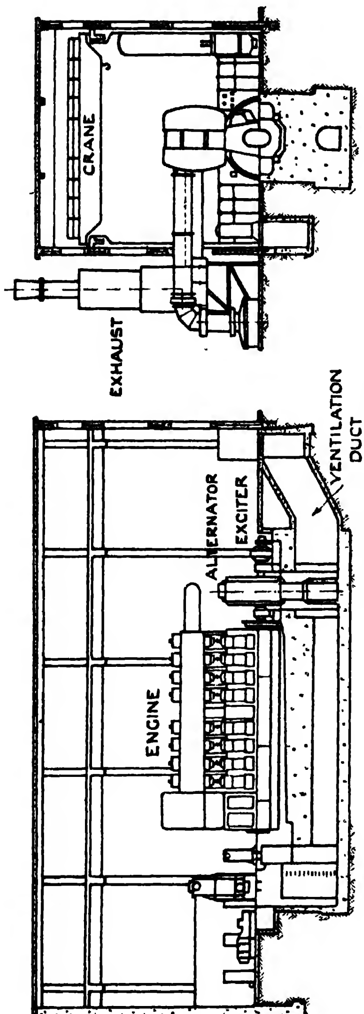

Fig. 614. Plant Layout (5·7 MW Set).

A Diesel-electric plant for a works, and inter-connected with a public utility system, is quite common, and the following particulars relate to a 2 MW installation.

There are six sets, each 330 kVA., driven by 12-cylinder, 4 stroke-

cycle, compression-ignition engine rated at 400 B.H.P. running at 1,000 r.p.m., with cylinders of 7-in. bore, 7¾-in. stroke. They have water-cooled exhaust manifolds, one for each bank of cylinders, and each outlet has its own silencer. These two sets of cylinders are arranged with an included angle of 60 degrees. The cooling water for the jackets and manifolds is handled by a common system, comprising two sets of Heenan fan-draft coolers, one of which suffices for normal winter loads. Each cooler has its own circulating pump

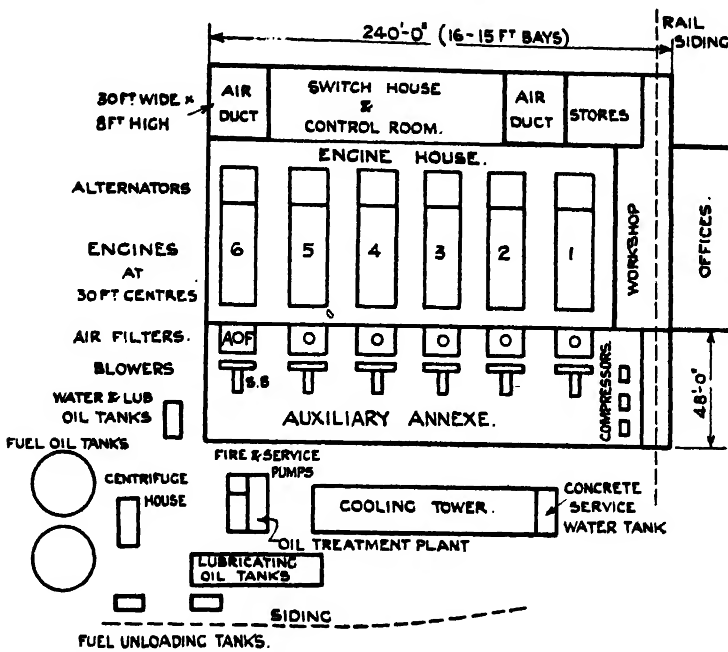

FIG. 615. Plant Layout, 36 MW Station.

rated to handle 24,000 gallons per hour (10 B.H.P. motor), and appropriate equilibrium tank, air outlet ducting and axial flow fan.

Fuel oil tanks are of welded steel construction and have a capacity of 25,000 gallons at working level, which is sufficient for one month's operation. Each engine has a daily service tank and fuel filter. Fuel pumps, one for each engine, are grouped into two self-contained units on each engine. Speed control is dependent upon a centrifugal governor operating through hydraulic Servo-mechanism on the pumps ; oil from the lubricating system is used

by the Servo-device. Engine starting is from individual 24-volt batteries.

Figs. 617 and 618 show further layouts.

CIVIL ENGINEERING WORKS AND BUILDINGS

Sites for Diesel-engine stations are usually chosen so as to be near to the centre of gravity of the electrical load, providing other conditions are favourable. It is desirable that good rail or road access is available for the transport of fuel oil, and that the site has satisfactory sub-soil properties. If the station is to be interconnected with a large electrical system, then it is an advantage if a primary sub-station is at hand. The engine and alternator are usually placed on a large concrete block, possibly reinforced where conditions justify this being provided. The depth of the foundation depends on the site conditions, and also on the size of the engine to be installed. In practice, the depth may vary from about 8 ft. to 12 ft.

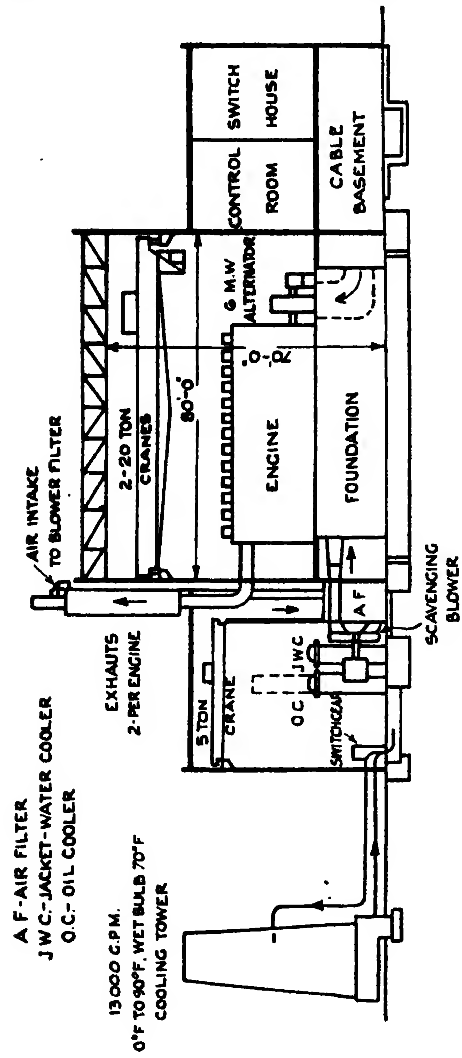

FIG Cro Fig 515).

The two essentials for a first-class foundation are: (1) the subsoil upon which the foundation will rest must be solid and firm, and (2) good workmanship, using the best materials available. Particulars regarding size

of engine foundation block, position and size of chases required for foundation bolts, are given by the makers. The foundation

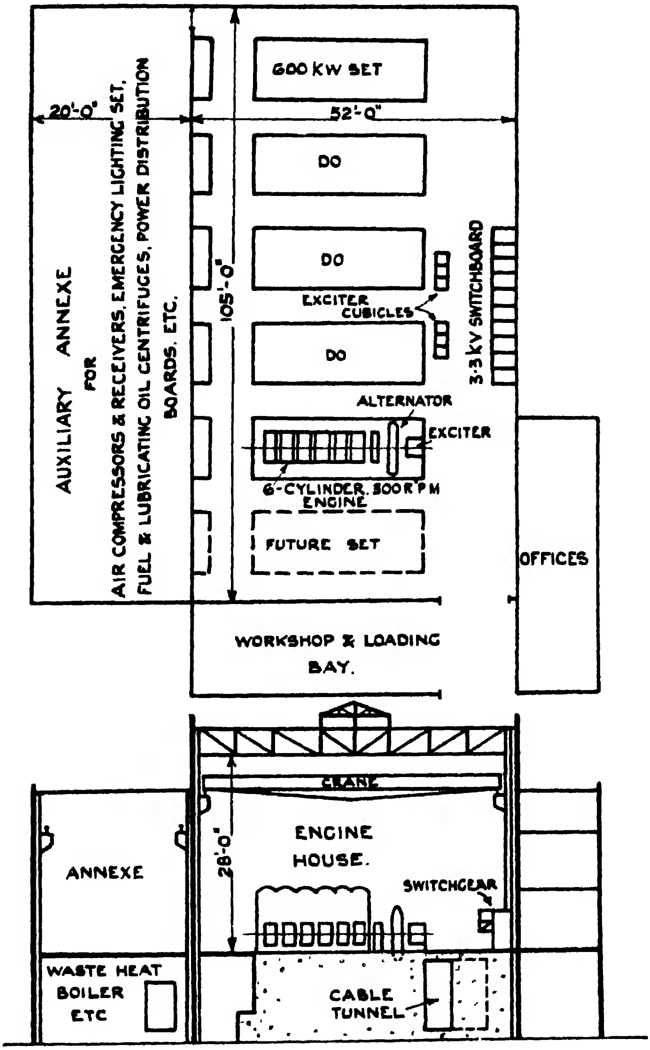

FIG. 617. Plant Layout, 3·6 MW Station.

bolts should not be fixed in the concrete until the engine bedplate has been placed in correct alignment. Good quality sand and cement should be used for grouting, and allowed to set before continuing work on the erection of the engine. Grout for running

under the bedplate should be a mixture of equal parts sand and cement, and should be fed, using iron rods for the purpose of breaking up any air pockets and ensuring that the grout is well packed. Packing plates should be well grouted, to prevent any tendency to work loose. Special care may have to be taken to prevent the transmission of vibration to the buildings or surrounding property. Information concerning such cases is given in Vol. I, Chapter II.

Buildings. The construction is similar in many respects to

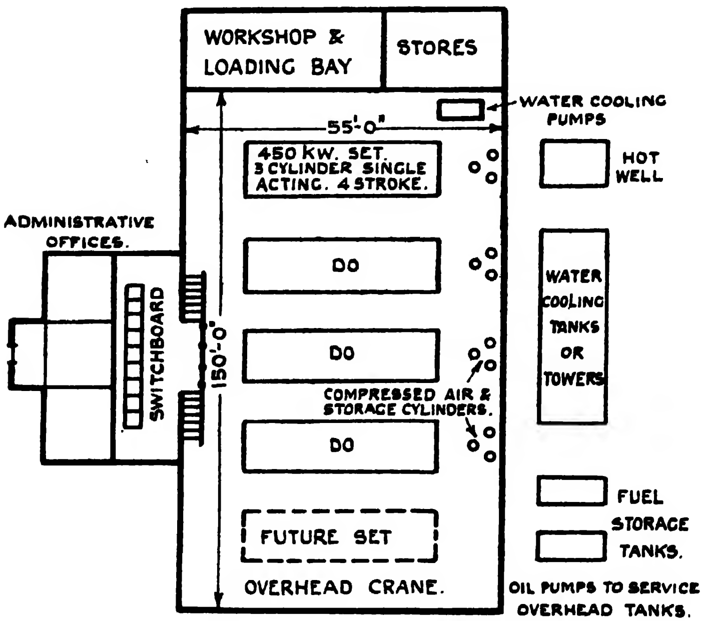

FIG. 618. Plant Layout, 2·25 MW Station.

buildings used for steam power plants, although on a much smaller scale. A steel frame with brick panels and asbestos-cement-sheet roof is quite satisfactory. Good natural lighting can be provided by including large vertical or horizontal windows in the side walls, and rows of skylights in the engine house roof. A workshop can be placed at one end of the engine house, with a rail siding or roadway running across or through it, so that the crane can be used to unload direct from the wagons.

The accompanying illustrations show the relative positions of the various buildings. In some stations provision may be made

in the auxiliary annexe for future gas compressors should natural gas be available.

The ventilation of a large engine house in hot climates is not an easy matter, and forced ventilation with air washing may be necessary. The main intake ducts are usually placed in the basement wall at the alternator side of the building. These ducts supply air to the alternator pits and to gratings in operating floor for normal building cooling.

MECHANICAL PLANT

There are two types of oil engine used for power station service namely, Diesel, and semi-Diesel.

In the first the fuel oil, which may be crude oil, is sprayed into the cylinder on the forward stroke, and ignited by high temperature caused by the extremely high compression of the air charge during the previous back stroke. There is, therefore, no actual explosion as is the case in ordinary oil, gas and petrol engines, and no carburettor, vaporiser or igniter is required.

The second is sometimes referred to as the "hot bulb" or surface ignition engine, and can operate on crude oil, tar oil, sewage gas, or any other fuel which can be used in Diesel engines. Its thermal efficiency is almost as high as that of the latter, and the distinctive feature of it is that the compression pressure is lower than in the Diesel engine (probably 350 p.s.i. compared with 500 p.s.i.); hence, the temperature reached by compression alone is not sufficient to ignite the fuel. A blow-lamp or electric ignition device can be used when starting the engine, and the combustion of the working fuel then maintains a special chamber or surface sufficiently hot to ignite the compressed charge.

The Diesel Engine Users' Association have recommended the following abbreviations which are helpful when comparing engines:—A—air-injection; M—mechanical injection; V—vertical; H—horizontal; O—open crank; E—enclosed crank chamber; 2—two-cycle; 4—four-cycle; P—pressure charged; C—cooled pistons; G—gas-fuelled. Each engine has three valves; fuel inlet, air inlet, and exhaust; and an additional air starting valve. These valves are all controlled by springs and may be actuated by cams from a half-speed shaft. The four-stroke engine has a slightly higher efficiency, but the two-stroke is cheaper, occupies less space, and has fewer working parts.

Four-cycle Engine. On the downward stroke (first cycle) air is drawn from the atmosphere through the air inlet valve in the cylinder cover. At the bottom of the stroke the cylinder is full of air and ready for compression.

On the upward stroke (second cycle) the air is compressed to about 500 p.s.i. with all valves closed. During the early portion of the next downward stroke (third cycle) fuel oil is injected into the cylinder in the form of a spray, by an air blast at about

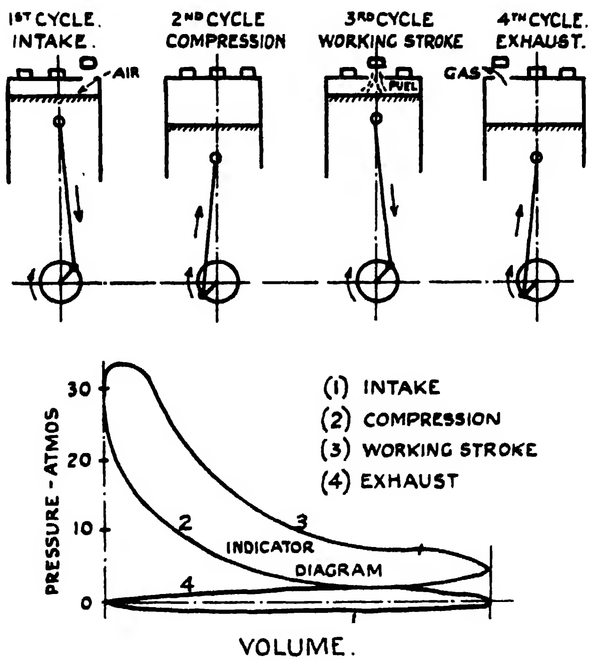

FIG. 619. Four-stroke Cycle.

1,000 p.s.i., through a needle valve which atomises it before entry into the cylinder. As the temperature of compression is above the flash point of the fuel oil, combustion takes place. After the fuel oil valve closes, expansion takes place, and just before the end of the stroke the exhaust valve opens. On the following upward stroke (fourth cycle) the exhaust valve opens, and the products of combustion are blown out of the cylinder. The action of the four-stroke cycle will be noted from Fig. 619. The advantages claimed for this cycle are :—

(1) Cylinder scavenging is performed throughout one stroke; hence, more efficiently done and the fuel consumption is slightly less.

(2) Scavenging pumps are unnecessary.

(3) Combustion and expansion occurs once in four strokes; therefore, the cooling is better and the heat stresses are lower.

(4) As expansion is continued until almost the end of the stroke in the two-stroke cycle, the exhaust ports are uncovered for almost 80 per cent. of the stroke; hence, in the last 20 per cent. of the stroke the work done is quite small.

(5) There are no ports in the cylinder liner, which are usually a source of weakness, with hot exhaust on one side and cold scavenge air on the other.

(6) Lubrication is more effective, and during suction and exhaust strokes, the pressure on the main gear is relieved; hence the oil film automatically reinforces itself in the bearings, etc. The engine can thus be designed with higher bearing pressures.

Two-cycle Engine. Consider piston at the bottom of the stroke (first cycle), the cylinder is full of air at nearly atmospheric pressure; on the upstroke air is compressed to about 500 p.s.i. During the downstroke (second cycle), combustion, expansion, exhaust and filling of the cylinder with clean air have to be effected. Fuel oil is sprayed into the cylinder during the early part of the stroke, as in the four-cycle type. The fuel oil valve then closes, and expansion occurs until last part of the stroke, when the exhaust ports are uncovered by the piston. Ports in the opposite side of the cylinder are next uncovered, and air from a scavenge pump enters the cylinder at about 1 to 4 p.s.i., expelling the products of combustion from the cylinder and refilling it with clean air ready for compression. Fig. 620 depicts the action of the two-stroke cycle engine.

The advantages claimed for this cycle are :—

(1) More power can be developed for a given size of cylinder.

(2) The weight, cost and size of engine per B.H.P. is less.

(3) More flexible engine, as the turning effort on crankshaft is more even for a given number of cylinders which is an advantage at low speeds.

(4) Usually a simpler design of cylinder cover.

Size of Engine. The horse power of a steam engine can be increased considerably above the rated output by delaying the cut-off, thus admitting more steam to the cylinder, and raising the mean

effective pressure. In internal combustion engines, however, it is impossible, except by supercharging, to greatly increase the weight of fuel burned beyond the value corresponding to the normal output for which the engine is designed.

At higher altitudes a larger engine is required; at 8,000 ft. the loss of power amounts to 20 or 35 per cent. in oil and gas engines, or approximately 3 to 4 per cent. per 1,000 ft. over 500 ft. above sea-level. In hot climates, even when allowance is made for altitude,

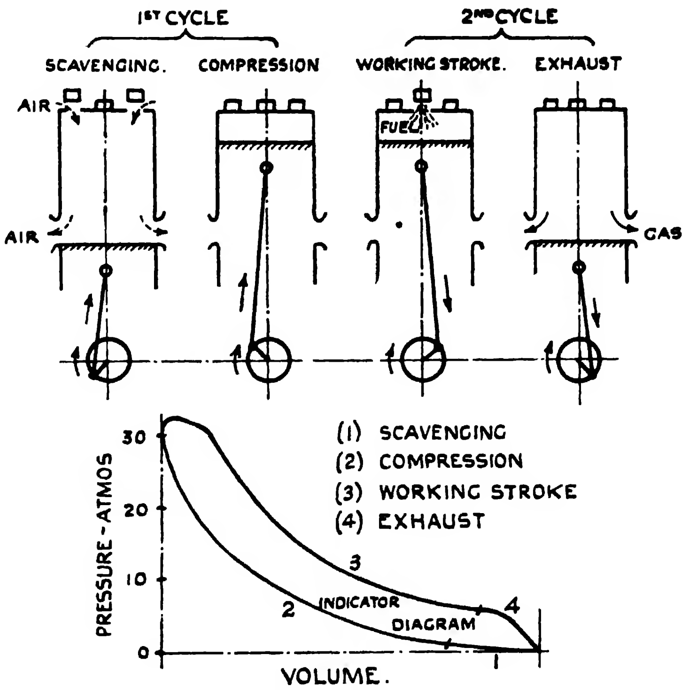

FIG. 620. Two-stroke Cycle.

oil engines will not continue to give their rated output, owing to the high temperatures and the consequent decrease of mass of the volume of air in the cylinder. The loss may amount to about 1 per cent. for each 6° F. above 60° F. Some makers allow 1 per cent. for every 5° F. above 90° F. Though all engines show to best advantage on steady load at or near full-load rating, the relative increase in fuel consumption at partial loads (Fig. 621) is no greater than in steam plants. As the majority of engines work on fluctuating loads, probably between 60 to 70 per cent. of full load, this

flat consumption curve ensures economical operation under average working conditions, which is more important than a low specific fuel consumption at full load only. Other features are that the minimum value does not lie close to the full-load figure, and the curve does not rise suddenly beyond this point. These indicate a good mechanical efficiency and a conservative rating.

$$\text{The B.H.P. of an engine} = \frac{\text{PLANE}n}{33{,}000}$$

where P—indicated mean effective pressure, p.s.i.
L—length of stroke, ft.
A—area of each cylinder, sq. in.
N—speed (N/2 for four-cylinder engines), r.p.m.
E—mechanical efficiency.
n—number of cylinders.

In the four-stroke cycle there is one impulse in every four strokes or two revolutions ; whereas, as in the two-stroke cycle, there is one impulse in every two strokes or one revolution. In practice, cylinders are standardised to cut down production costs. The piston speed and the mean effective pressure can be varied within certain limits, and hence the maximum and minimum power per cylinder, together with the speeds for each standard size, can be tabulated. The average piston speeds are higher than in steam engine practice, for higher cylinder pressures require expansion and compression to be done at a quick rate to reduce leakage past the piston. Values appear to vary between 700 to 1,200 ft. per minute, the average being 800. The piston speed V = 2 L.N. and the piston diameter $d = \frac{L}{R}$. Substituting for L, then $d = \frac{V}{2\text{ N.R.}}$

The mean effective pressure with atmospheric induction varies between 85 to 100 p.s.i., the average normal working pressure being about 90 p.s.i. With supercharging the average figures vary from 110 to 125 p.s.i.

The considerations affecting stroke bore ratio $\left(R = \frac{\text{stroke}}{\text{dia.}}\right)$ are : cylinder cooling surface, piston load, and scavenging. The surface for radiation should be as large as practicable, but the piston load would be excessive, and for an average size of engine a short stroke would increase the cost. A very large value of R will reduce scavenging efficiency, and average values appear to be between 1·7 to 2·1.

By supercharging, the outputs of Diesel engines can be increased up to 50 per cent. above their scheduled ratings. Supercharging consists of introducing into the cylinders more air than would normally be drawn in by the pistons. This makes it possible to obtain good combustion with a greater quantity of fuel, and thus, by running on higher mean effective pressures, enables an engine of a given size to produce more power. The cost of supercharging equipment is such that the price per horse power of a supercharged engine shows only a small saving against a standard engine. Supercharging is, however, especially suitable when it is desirable to fit the highest output engine into a small space, or for engines working at high altitudes. For continuous, twenty-four hours per day working, the maximum continuous output of an engine should not exceed 90 per cent. of its scheduled rated output. The scheduled

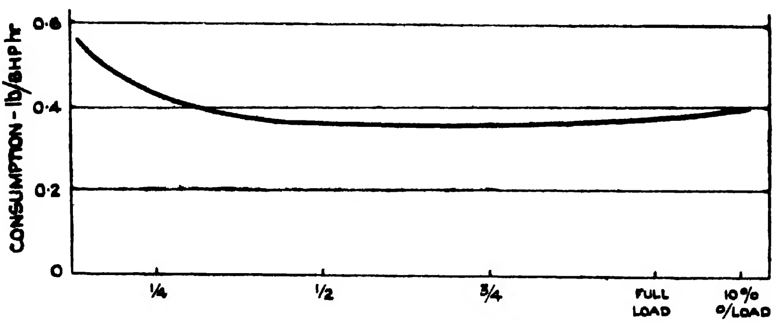

FIG. 621. Fuel Consumption Curve.

outputs are usually obtained when the engines are running at their rated speed in an ambient air temperature not greater than 90° F. at an altitude not exceeding 500 ft. above sea-level, and when using fuel of the usual characteristics, free from impurities, having a specified gross calorific value. The engines are generally capable of developing an overload of 10 per cent. for one hour.

Design and Constructional Details. The number of cylinders for any given engine is fixed by the output desired, the space available, and balancing and torque considerations. As the number of cylinders increases, so does the weight, cost, and space occupied, and number of working parts. Engines with up to eight cylinders are used. The principal forces acting on the engine are : piston load, and inertia. The engine frame is designed to resist the piston load, and the guide thrust, and, as forced lubricant is used, the frame must entirely enclose the working parts of the main gear.

The principal features in cylinder design are: strength combined with freedom for expansion, efficient cooling, and correct materials. A liner is fitted in each cylinder, and all parts which are in contact with the hot gases (products of combustion) should be as thin as possible and swept on the outside by water or other cooling medium. Special cast iron is used, which has high tensile strength, is hard, and has good machining qualities. High tensile strength permits the use of thin walls, with consequent high heat transfer rate and improved cooling. The harder the material, the less wear, whilst resistance to growth is also important to avoid piston seizure. Growth appears to be due to oxide of silicon formed by the gases entering the pores of the material and attacking the silicon, and causing the cylinder surface to swell. Silicon is necessary for good machining, and manganese is added to close the pores and so prevent silicon from attack.

To permit expansion and contraction, the liners are fixed at the upper end only, and are made a light fit in the crank case to prevent distortion or difficult withdrawal. The cylinder heads are of heat-resisting cast iron with machined seatings for the inlet, exhaust, and air-starting valves for the fuel injector. These requirements will depend on the type of engine used. The cooling water is taken from each cylinder jacket to the cylinder head by external connections. The water flow is directed towards the exhaust valve and fuel injector casings, thus providing good circulation of the cooling water to all important points, and eliminating vapour pockets.

The engine is mounted usually on a cast iron bedplate which, for the larger sets, may be in two or more sections bolted together.

A solid forged crankshaft of adequate proportions and large bearing areas is provided, and for engines having six or more cylinders it is usually in two sections. The crank case is of special cast iron and of rigid construction, and designed to give complete access to the main and large-end bearings. It is usually in two pieces for the larger engines, and inspection doors are included to afford access to the cooling water spaces for cleaning.

The ventilation of crank cases has been the subject of much discussion in view of the possibility of explosions. In some engines an exhaust fan is fitted, which delivers the vapour into a pipe and then *vid* an oil trap before being vented to atmosphere. An analysis of explosion records show that, in the main, explosions have taken place when a scavenging blower, or a separate exhaust fan. has been

used, whereas no explosions are recorded on engines which have had no positive means of scavenging the crank case, but were fitted with breathers, or left open. The breather should be fitted at the highest part of the engine, and to prevent oil vapour contamination of other equipment, it should be extended into the roof and terminate with a U-bend and a corrosion resistant wire gauze to act as a flame arrester. The results of experiments and observations have led to the following recommendations :—

(1) Crank case should not be ventilated by a blast of air.

(2) Crank case, if hot, should not be opened until at least ten minutes after shutting down.

(3) Explosion relief valves should be fitted on all engines having cylinders larger than 8 in. diameter.

(4) Explosion relief valves should be of the return-seating type, and should relieve the pressure readily and close rapidly to prevent an inrush of air.

(5) Relief valves should have a free area of about 1 sq. in. per cu. ft. of crank-case volume, and should be placed at or near the ends of the crank case.

(6) Natural ventilation, through breathers, on enclosed crank cases, is in order.

An accumulation of oil vapour, when finely divided in a crank case, can be highly explosive, although normally over-rich and not easily ignitable. It has been suggested that a crank-case explosion consists of a primary explosion of little consequence, followed by a secondary explosion due to the inrush of air if there has been an opening caused by the first. With regard to the opening of crank-case doors, experience tends to suggest that an explosion may be caused by an inrush of fresh air diluting what was otherwise an over-rich mixture.

The pistons are of special heat-resisting cast iron, ground to graduated clearances which in practice have proved satisfactory in respect of maximum heat transfer with minimum friction. Pressure and scraper rings are fitted to suit the design and ensure adequate lubrication. The piston in the normal vertical trunk engine operates under severe conditions. It must not only withstand the firing pressures, heat stresses and dynamic loading, but it also serves the purposes of a cross-head under conditions where lubrication is of the boundary type. The clearance volume or space is of definite shape and volume, and is usually determined by experiment.

The compression ratio $= \frac{\text{clearance volume}}{\text{swept volume}}$ and varies between 0·08 to 0·122 (13 to 14/1 are common) according to the design. There are various designs all of which aim at preventing the incoming oil spray being cooled by contact with the piston before combustion has taken place. Such a condition would result in imperfect combustion. In some designs the piston crown is machined to a special shape to assist complete combustion.

The gudgeon pins are of case-hardened steel, and may be of the floating type and arranged for lubrication over the entire length of the bearing surfaces. Caps secured to the piston bosses provide an oil-tight joint, and locate the pin. A cast iron flywheel is provided, and is designed to give the specified speed regulation, while a rack cast in the rim permits of barring or turning of the engine.

The camshaft runs in forced lubricated bearings and is driven from the flywheel end of the crankshaft by a roller chain or other means. The inlet and exhaust valve cams may be of steel, case-hardened on the working surfaces, or of chilled cast iron. The fuel injection cams are of steel, case-hardened on working surfaces.

The connecting rods are made from 35-ton steel and machined all over, and also of H-section drop-forgings.

The exhaust valves are of a high-grade heat-resisting steel with hardened thimbles fitted to the inlet and exhaust stems, and the striker ends of the levers are also hardened. Two springs are provided for each inlet and exhaust valve, to reduce the risk of spring failure. The fuel injector and air starting valves are automatic in action and are opened by the pressure of the fuel and starting air, respectively. A pressure relief valve is fitted in each cylinder head. The valve gear is lubricated from the pressure system.

Governor Gear. A centrifugal governor having a high degree of sensitivity is driven from the camshaft through bevel gears and operates directly on the fuel injection pumps. The governor is capable of speed adjustment to 5 per cent. above or below the normal engine speed, by hand regulation while the engine is running. In one design, the standard variation in speed, on sudden application or removal of full load, is 7 per cent. momentarily, and 4 per cent. permanent, but special governing characteristics can be included The governor gear shuts down the engine if the lubricating oil pressure fails.

Fuel Oil System. An overhead fuel service tank is provided, which includes a strainer, and the fuel is taken through a duplicate cleaner to the system. A fuel pump fitted close to the fuel injector and operated from the camshaft, is provided for each cylinder. Each pump can be adjusted separately, so that correct distribution of load over all cylinders can be maintained. Hand priming of the fuel injection system is also included. The fuel injector fitted in the cylinder cover maintains good atomisation over long periods. Fig. 622 shows a fuel-oil system for a large Diesel plant. At con-

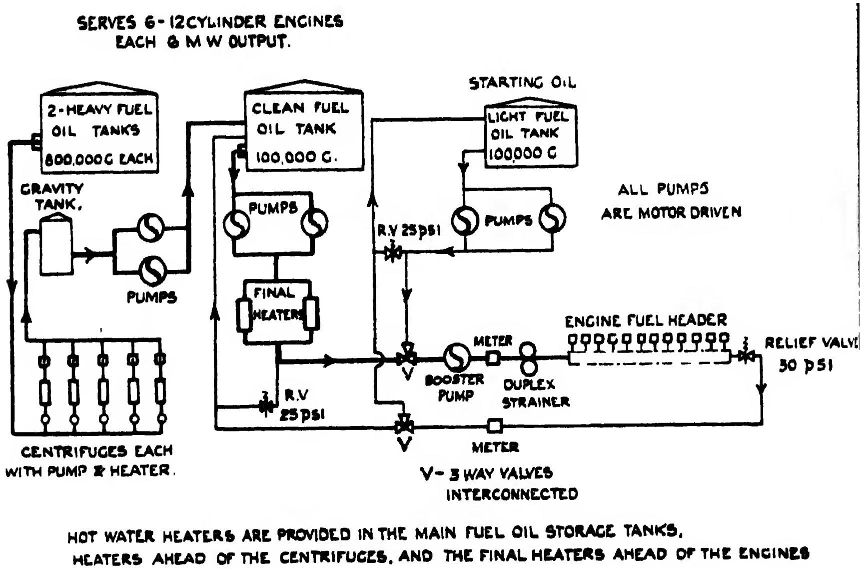

Fig. 622. Engine Fuel-oil System.

tinuous full load this plant consumes five tankers of fuel daily. Bunker-C fuel oil is pumped into two storage tanks, and light oil for starting, also lubricating oils, are received by rail tanker.

The clean-fuel piping is of copper with sweated copper fittings, tin-antimony soldered. Hot fuel pipes are insulated with rock wool blankets, formed on site and finished with a coat of hard-setting cement. Disc type fuel meters are included in flow and return pipes to each engine, to provide routine efficiency checks. Changeover from heavy to light fuel, or *vice-versâ*, which is necessary when starting or stopping an engine, is done by coupled three-way valves placed near the engine. By running for a short time on light

oil before closing down, the clogging of pipes, fuel pumps, etc., is prevented.

The fuel-oil store for a six—600 kW. plant contains four—6,500 gallons steel storage tanks. Pumps in the engine house annexe transfer the fuel as required to a daily supply tank, from which it gravitates to the individual engine service tanks. The fuel can be passed through a centrifuge in its passage between these tanks, and the fuel to each tank is metered.

Lubricating Oil System. Automatic pressure-feed lubrication is provided by a gear-type pump, which is driven from the crankshaft, and delivers oil under pressure from the oil tank through a fine-mesh duplicate strainer and an oil cooler to a main pipe inside the crank-case. Connections are made from this pipe to the crankshaft main bearings and all other sections of the plant requiring lubrication. The pistons are lubricated by oil vapour from the crank chamber. A hand priming pump is included to enable oil to be supplied to all parts before starting the engine.

Fig. 623 shows the principal circuits for a large plant.

The working pressure varies between 20 to 30 p.s.i., and should not fall below 12 to 15 p.s.i.

In America extensive use is made of inhibited treated lubricating oil, and this is largely a result of high engine temperature.

The treatment of oil has been given careful attention and in one plant the oil is pumped out of the engine sumps every 400 hours and run into a tank half filled with water. The dirty oil is then heated to boiling point by means of a steam coil, after which it is allowed to cool and settle. Test taps are fitted to the settling tank at various heights to test when water appears. After drawing off all the settled sludge and water, the oil is forced through a paper pack filter. This procedure increases the life of the packs by three times. Another tank has heating elements, and when pistons are withdrawn, they are dropped into this tank, which contains 8 to 12 oz. per gallon of a carbon softening solution heated to about 170° F., and if the rings are fast, or much carbon is deposited, they are left in overnight.

Water Cooling System. A water-jacketed exhaust manifold is fixed to the cylinders, and if the heat of the exhaust gases is to be utilised, a non-jacketed but lagged manifold can be fitted.

The water cooling system employed depends on certain conditions, and the gravity system is satisfactory if an ample water supply is available, but cooling towers, spray ponds, and cooling

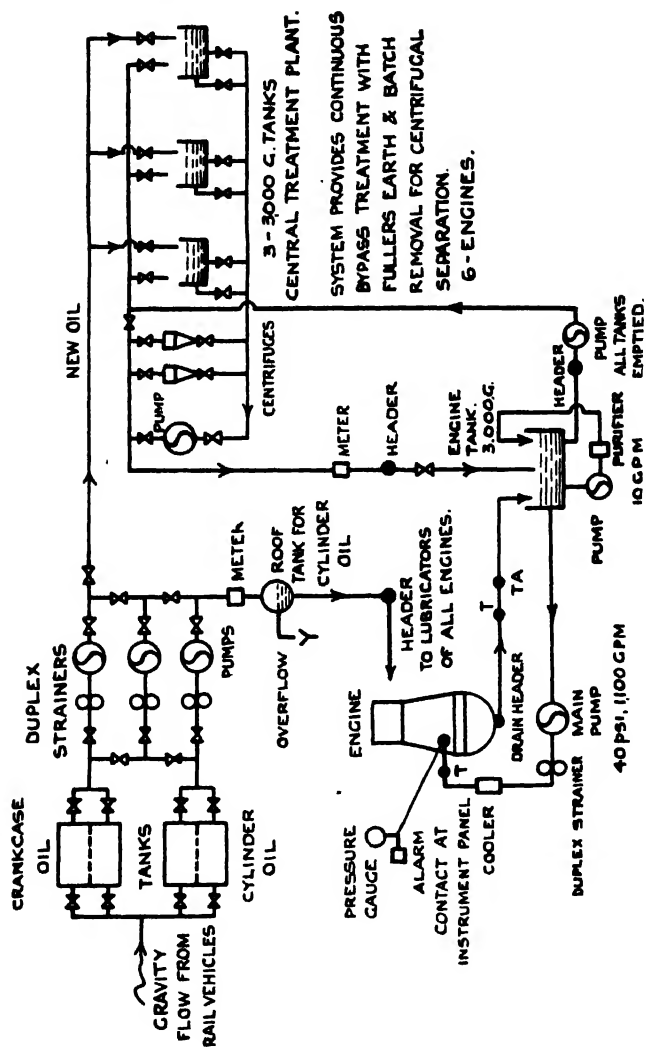

Fig. 623. Engine Lubrication System (Six–6 MW Sets).

tanks can be adopted (Fig. 624). The water should always enter the jacket at the bottom and leave at the top, so as to ensure that the jacket is always filled. Cooling tanks are used for smaller engines, the circulation of which depends on the "thermosyphon" principle, or being assisted by a pump. Without a pump, the force producing circulation is the difference in weight between the columns of hot water leaving the jacket and the column of comparatively

cool water returning from the tanks. This force is made adequate by raising the tanks above the engine cylinder. Circulating tanks are sometimes connected at top and bottom, but the arrangement calculated to obtain the most effective cooling is to connect the top of one tank to the bottom of the next. The same result is obtained by means of an internal pocket as shown in Fig. 625.

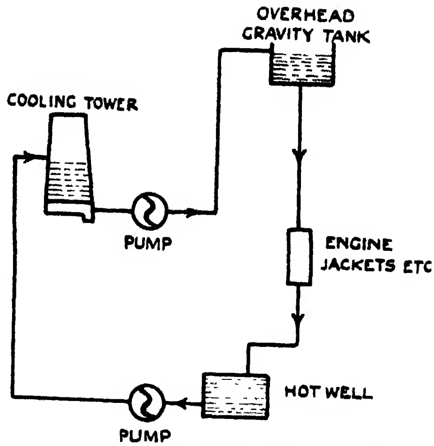

FIG. 624. Gravity Cooling Water System.

A circulating water pump can be driven from the crankshaft or, alternatively, an independent pump driven by electric motor can be used. The water is first taken to the oil cooler, and then by way of a main pipe to

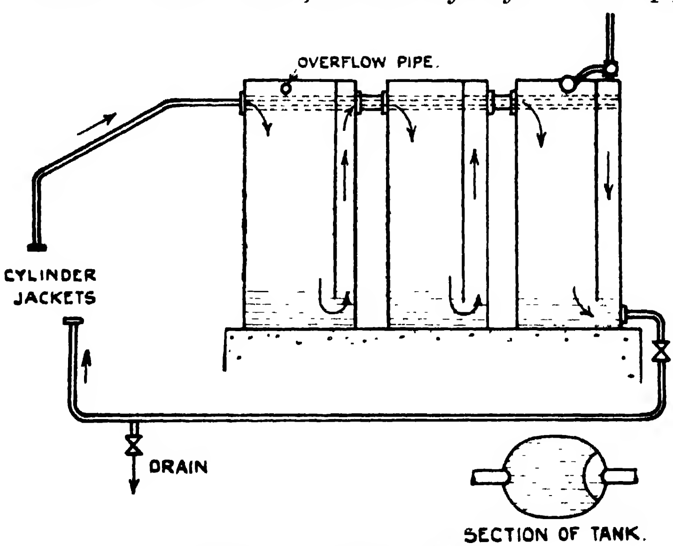

FIG. 625. Cooling Tank Layout.

the water jacket on each cylinder. By means of external connections, the water is then led to the cylinder heads, where the flow is directed towards the exhaust valve, and fuel injector casings.

A separate outlet is provided from each cylinder head, which is connected to a common outlet pipe which can have connections to the jacket of the exhaust manifold.

Fig. 626 shows the main circuits and connections for one plant. The water supply is taken from two wells on the station site, and is treated before passing into the cooling water and heating systems. The run-off water from the cooling tower system is adjusted to limit the total alkalinity in the circulating water to double that of the make-up. The cooling water is treated with 3 p.p.m. Calgon to control scaling in the various heat exchanger tubes, and it is

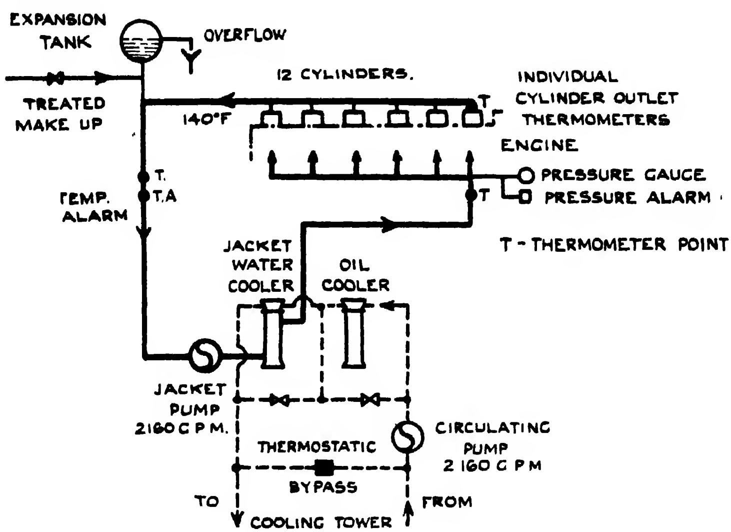

FIG. 626. Engine Cooling Water Arrangements (6 MW Set).

also chlorinated once per shift up to 6 p.p.m. to prevent algæ growths which would cause rapid tube fouling. Make-up water for the jacket-water system of each engine, and for the hot-water fuel-oil heating system, is taken from the service water tank. A 120 g.p.m. Zeolite unit softens the make-up, which is further conditioned with caustic soda to yield a *p*H value of 9·5. For inhibiting corrosion, 300 p.p.m. of sodium chromate is also added. Treated water storage tanks have sufficient capacity to replace water in one engine. The presence of algæ growth on water cooling ponds and towers has been checked by suspending a sheet of copper 3 ft. × 2 ft. from a galvanised water pipe in the cooling water. In temperate climates the water outlet temperature on full load

should be regulated between 120° to 140° F., and in tropical climates 130° to 150° F. Water outlet temperatures should not be allowed to exceed 180° F. Any water not absolutely soft will cause deposits at a temperature of about 120° F. Corrosion and scale formation are detrimental to efficient operation. Effective cooling becomes impossible, engine wear is accelerated, fuel and lubricating oil consumption increases, and overheating results. Some makers consider that a two-stroke engine should be run at a somewhat higher temperature than the four-stroke. For engines with cooling water pumps, the quantity of water circulated varies according to the design of the engine, and is about 5 to 8 galls./B.H.P./hr. for temperate climates, increasing by 100 per cent. for semi-tropical, and 200 per cent. for tropical climates.

It is sometimes assumed that if the cooling water leaves the jacket comparatively cool, there can be no danger of over-heating. This, however, is not necessarily a criterion, as a low temperature of water may indicate that the jacket is scaled up. A given amount of heat has to be dissipated in some way and if, owing to scale, it is not transferred to the cooling water, the result is that the liner and piston become overheated. The cooling pump should be run for some time after the engine is shut down, and so avoid excessive water temperatures and prevent heavy scaling.

Waste Heat Recovery. Where a supply of hot water or steam is required for building or fuel-oil heating or process purposes, it is possible to effect economies by utilising the waste heat in the jacket water and the exhaust gases. With combined jacket and exhaust recovery, an overall thermal efficiency approaching 80 per cent. can be realised under favourable conditions. Fig. 627 shows a hot water system for fuel-oil heating.

It is estimated that in many cases some 40 per cent. of the heat in the fuel-oil can be recovered.

Typical exhaust gas temperatures are :—

	Degrees F.
100 per cent. load	760–800
75 ,, ,, ,, ...	610–650
50 ,, ,, ,, ...	460–500

It is recommended that even on overload the temperature should never exceed 900° F., and if the exhaust temperature of any one cylinder should vary by more than 50° F. with any other cylinder, investigations should be made for the cause.

One authority has stated that from 1·2 to 1·5 lb. of steam (from and at 212° F.) at 100 p.s.i. (gauge) can be generated per B.H.P. per

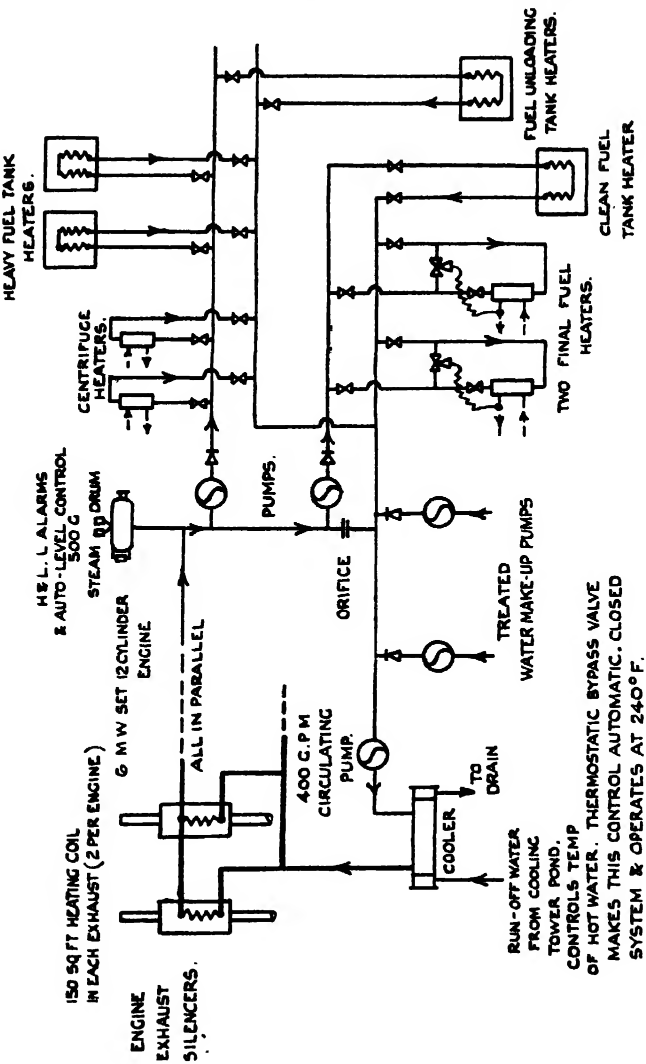

FIG. 627. Fuel Oil Heating System.

hour. Weight of gases from a Diesel engine can be taken on the average as 13 to 16 lb. per B.H.P. per hour at 750° F.

Engine Starting Equipment. This includes an air compressor and receivers external to the engine where air at a pressure of 250 to 350

p.s.i. is not at hand. One starting equipment can be arranged to serve all the engines installed. The compressed air is taken from the receiver to a mechanically-operated air distributor driven from the camshaft. The distributor admits air at the correct time to the cylinders through the automatic air starting valves included in the cylinder heads. The master valve controlling the air to the distributor, the hand speed regulator, and the fuel oil control, can be grouped to simplify engine control. Interlocking the starting lever and the barring gear for turning the engine when shut down, prevents admission of starting air if barring gear should be engaged.

For automatic starting, the ordinary air starting equipment is arranged to open in the correct sequence and close when the engine is running The automatic starting mechanism is also arranged to prime the lubricating oil system, and to do the required operations in connection with the supply of cooling water, and also make circuit on the electrical side.

Load Sharing of Cylinders. The load carried should always be evenly distributed over all cylinders; this can be checked by taking readings of the maximum pressures in the cylinders and exhaust temperatures at each cylinder outlet. Recommended maximum pressure at full load appears to be of the order of 750 to 780 p.s.i.

Opposed Piston Engines. These are of various types and vary in detail according to the make. The English Electric Company's Fullagar Diesel engine is typical, and is, in effect, a double-acting two-stroke-cycle engine without cylinder covers. In other opposed-piston engines, no less than three cranks per cylinder are necessary, whereas the Fullagar engine has only one crank and connecting rod per cylinder. The principle of this engine will be understood from Fig. 628. Combustion takes place between the opposed pistons A and B, and causes B to move downwards and A upwards. Piston A acts on the right-hand crank through the rods, and also draws up piston D in the adjacent cylinder. Piston B acts directly on the left-hand crank, and draws downwards the piston C in the adjacent cylinder. The power for compressing the air in the combustion chamber is thus obtained directly from the pistons in the adjoining cylinder, instead of having to be transmitted through the crankshaft, as in other types of engines. The crankshaft receives two equal and opposite impulses, and the side thrust produced by the tie-rods is taken by the cross-heads F and G.

The obliquity of the rods is small, and much less than the maximum obliquity of the connecting rods in the ordinary direct-acting engine. The lateral forces on the cross-head faces are, therefore, very small.

Since the pressure in the cylinders acts equally on the upper and lower pistons, the forces upon a pair of cranks are equal and opposite at all times, and the main bearings are therefore relieved

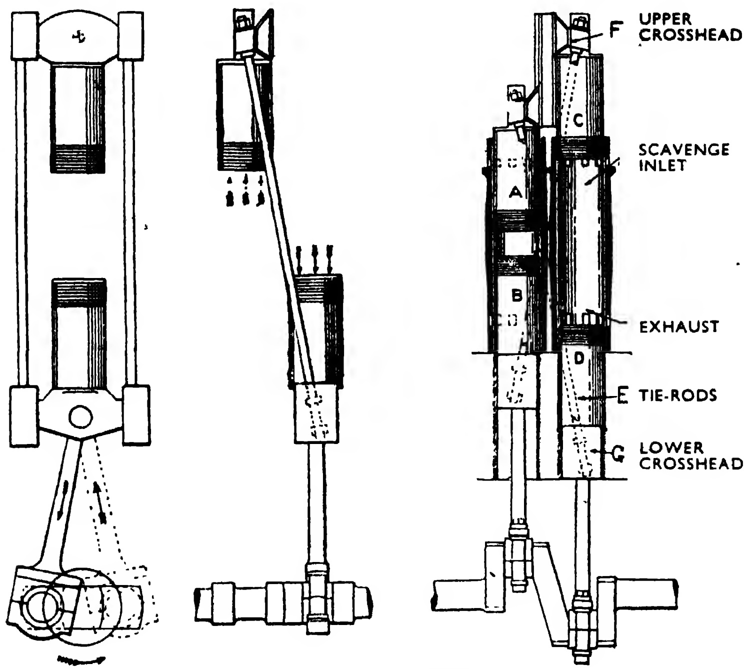

Fig. 628. Principle of Fullagar Engine. (English Electric Co.)

of load. The pressure between the pistons is taken wholly by the crossheads, tie rods, connecting rods and crankshaft; thus relieving the framing of all major stresses.

The reciprocating parts are cushioned at each end of the stroke, *e.g.*, the pair of connected pistons, A and D, are cushioned upon the down stroke by the pressure under piston A, and on the upstroke by the pressure above piston D. Each connecting rod is double-acting, and the effort of each crank is uniformly in one direction. A four-crank engine therefore receives four pairs of balanced impulses per revolution, eight in all, and the consequent effort is

more uniform than that of any other oil engine. Some of the advantages claimed for this engine are :—

(1) Very simple—no cylinder covers, exhaust valves, or mechanically-operated air-inlet valves.

(2) Good balance—even torque and, consequently, very small cyclic variations, even with a light flywheel.

(3) Small load on bearings—the reversals of forces on the crank-shaft, due to the simultaneous pull and thrust from adjacent connecting rods, brings about bearing conditions ideal for good lubrication.

(4) Low weight and small floor space per H.P.—It is estimated that there is a saving approaching 34 per cent. as compared with the usual four-cycle engine. While the height of the engine exceeds that of a four-cycle engine, only a small increase is necessary in the height of the crane.

(5) Highly efficient scavenging system—the exhaust and scavenge ports are placed at the opposite ends of the cylinder. Separate scavenge pumps or blowers are not required.

(6) Low fuel and lubricating oil consumption.

Typical Engine Data

Four-Stroke Cycle (Vertical)

B.H.P.	Number of Cylinders	Output. kW.
165	3	110
220	4	150
275	5	190
330	6	225
385	7	260
440	8	300

50 cycles per second ; speed 600 r.p.m. ; stroke 12 in. ; bore 10 in.

Four-Stroke Cycle (Vertical)

B.H.P.	Number of Cylinders	Output. kW.
500	4	345
625	5	430
750	6	520
875	7	605
1,000	8	700

50 cycles per second ; speed 375 r.p.m. ; stroke 20 in. ; bore 15 in. The power of any of these engines may be raised by 50 per cent. by the use of pressure-charging equipment.

Four-Stroke Cycle—Fullagar (Vertical)

B.H.P.	Number of Cylinders	Output kW.
980	4	680
1,470	6	1,020
1,960	8	1,360
Speed 300 r.p.m.;	stroke 16 in.;	bore 14 in.
2,450	6	1,720
3,275	8	2,300
*3,500	8	2,450
Speed 200 r.p.m.;	stroke 22 in.;	bore 19 in.

(* Speed 214 r.p.m.)

Instrumentation. A panel can be provided for each set with the following instruments incorporated :—

(1) Pressure gauges for starting air, lubricating oil before and after cooler, cooling water, jacket water, and fuel-oil before and after strainer.

(2) Multi-point temperature indicator for temperature of each cylinder and each exhaust manifold.

(3) Scavenging blower-motor load ammeter.

(4) kW. meter for alternator output.

Visible and audible alarms give warning in the event of :—low lubricating-oil pressure; high lubricating-oil temperature; low jacket-water pressure; high jacket-water temperature; blower motor overcurrent, and failure of lubricating-oil pressure. An audible alarm also sounds should the engine-driver attempt to start up under incorrect conditions. Should the engine overspeed, lubricating oil fail, or the scavenging air pressure fail, a spring-loaded device releases and turns the fuel regulating shaft to the "no-fuel" position, and trips the alternator main circuit-breaker simultaneously.

ELECTRICAL PLANT

The principal electrical plant consists of alternators, exciters, transformers, switchgear and auxiliaries, and the principles already enumerated under these sections apply in general to Diesel-electric plants. The accompanying diagrams (Figs. 629 and 630) show main connections, which can be modified to suit any special requirements.

Alternators and Exciters. The alternator is of the rotating field, salient pole type, special attention being paid to the mechanical design, so as to avoid the possibility of torsional vibrations being

set up by the inherently uneven turning moment of the engine. The regulation of the alternator is such that satisfactory parallel

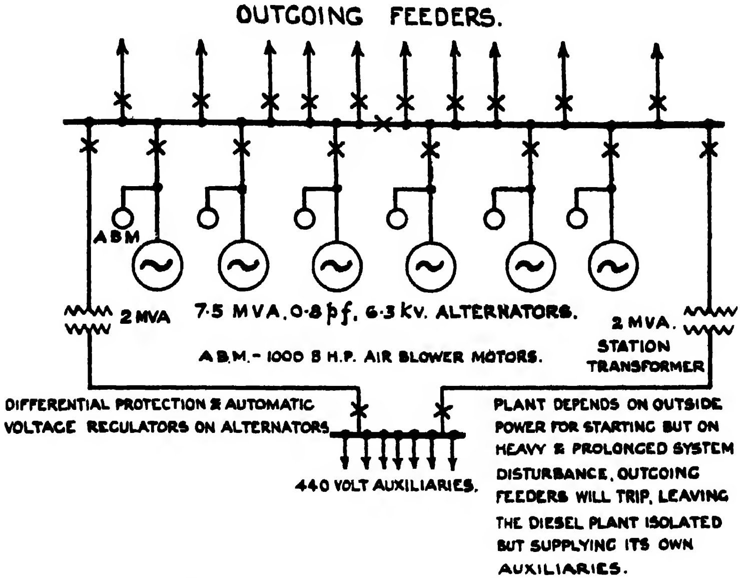

FIG. 629. Main Connections for 36 MW Diesel-electric Plant.

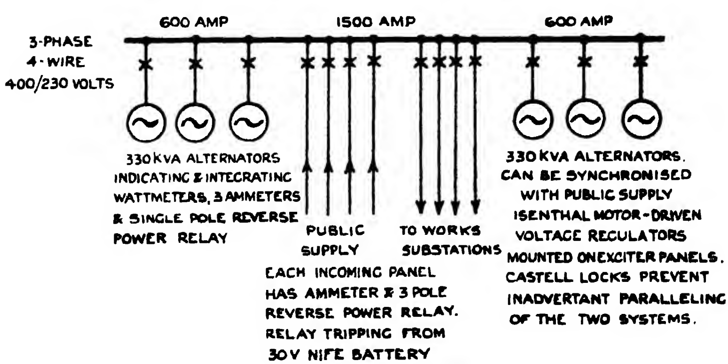

FIG. 630. Diesel-electric Work's Plant.

running and minimum shock to the machine under short-circuit conditions are obtained. Where close regulation is desirable, an automatic voltage regulator of the Tirrell or other type is included. The inherent regulation of standard alternators, *i.e.*, the percentage

rise in voltage above the rated voltage when full load is removed, is about 25 to 30 per cent. at 0·8 p.f., and 10 to 15 per cent. at unity power factor, assuming the speed and excitation remain constant.

The coupling of the alternator and engine should be rigid, to avoid torsional vibrations of a dangerous order at or near the normal running speed. If the two shafts were absolutely rigid under the torsional stress, the vibrations in the driving torque would only cause a slight periodic speed variation. The shaft system is not absolutely rigid, so that under the influence of torque variations, the system does not accelerate as a whole, but is thrown into a state of vibration. For this reason, it is advisable to avoid having a bearing between the flywheel and the alternator rotor. For sets of medium speeds and moderate outputs, it is usually possible to have a shaft of adequate size to provide a stiff enough connection between the flywheel and the rotor. The shaft has a half-coupling for connecting direct to the flywheel. In one case an unusual alternator construction ensured maximum stiffness with a long crankshaft of a 7 MW set. Instead of the usual hub pressed on the alternator shaft, the rotor disc, without a hub, clamps between the engine shaft flange and is held by fitted bolts. This design made it unnecessary to send the shaft to the alternator maker for assembly.

The stator frame is of fabricated steel construction, except for the smaller alternators the frames of which, together with end-shields, are of cast iron. The stator core is of low hysteresis loss, high silicon content, steel punchings, enamelled before assembly to reduce eddy current losses.

Lower-voltage alternators usually have former wound coils of cotton-covered rectangular wire, which are placed in semi-enclosed slots. For currents exceeding about 400 amps., bar-type windings are used. Higher-voltage alternators usually have former wound coils laid in open slots, rectangular wire being used for heavy currents, and round wire for relatively small currents. Where the overhang of the end windings is considerable, they are fastened to insulated steel rings, which are held by brackets fixed to the stator frame.

The rotor is of the salient pole type, the poles being bolted to a spider. The poles for small low-speed alternators are machined from solid steel billet, but for larger machines they are of laminated construction. Almost all Diesel-engine alternators are provided with damping windings. These consist of short-circuited copper bars embedded in the pole shoes, and the effect is that if there is

any momentary shifting of the field due to uneven torque, heavy currents will circulate in the bars in such a direction as to oppose the motion of the flux. These windings are fitted for emergency only, and are not intended to control conditions of resonance.

A direct-driven exciter is fitted and wound to provide an excitation voltage of from 90 to 150 volts. Various methods are used for supporting the exciter and coupling it to the alternator, and much depends on the size of the set. An exciter field rheostat is included for alternators operating at power factors from unity down to 0·8, but a main field rheostat can be provided if lower power factors are possible, and also where a very wide range of alternator voltage is required, or where fine control of voltage is desirable.

Parallel Operation. The parallel operation of Diesel-alternator sets calls for special care both by the engine and the alternator makers. An alternator requires an even turning moment, whereas the ordinary Diesel engine has probably the most uneven turning moment of all prime movers. In view of this, special care must be taken to ensure that there is no tendency for lights to flicker, and that hunting will not occur, due to resonance between the periodic disturbing forces of the engine and the natural frequency of the system. Therefore, to operate Diesel-alternator sets in parallel, certain specified conditions have to be fulfilled in respect of both mechanical and electrical problems.

The conditions usually specified are :—

(1) The cyclic variation shall not exceed a given value, probably $\frac{1}{150}$ to $\frac{1}{250}$.

(2) The maximum angular displacement from the mean position of rotation shall not exceed + or − $2\frac{1}{2}$ electrical degrees. Expressed in mechanical degrees this is + or $-\frac{5}{p}$ degrees where p is the number of alternator poles. The angular deviation is the amount the alternator moves ahead of, or lags behind, the position of uniform rotation.

It may be stated that 360 mechanical degrees correspond to $360 \times \frac{p}{2}$ electrical degrees, therefore, one electrical degree $= \frac{2}{p}$ mechanical degrees and one mechanical degree $= \frac{p}{2}$ electrical degrees.

In an A.C. cycle the current flows in one direction during the first half-cycle and in the opposite during the second half. Each time an

N-pole of the rotating field of an alternator passes from in front of a stator coil, and is replaced by an S-pole, the direction of the current changes. The distance between the centre lines of two adjacent poles, or the pole pitch, is equivalent to 180 electrical degrees, since the e.m.f. generated in the stator, as the field moves through this distance, causes the voltmeter needle to swing through 180°. Consequently, there will be two changes of current or a complete electrical cycle of 360° will take place each time the rotor advances through the angle subtended by a pair of poles. In an alternator shown in Fig. 631, the rotating field with six poles needs to turn only one-third of a revolution to complete one electrical cycle, with the result that there will be three electrical cycles for each revolution or a complete cycle of the mechanical rotor.

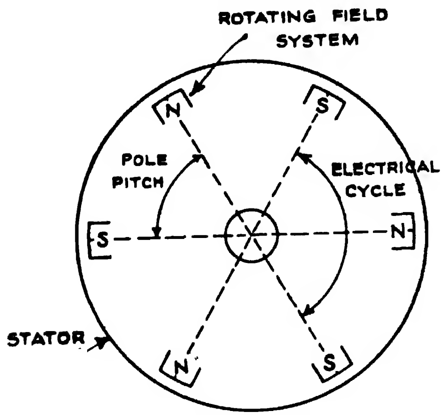

Fig. 631. Six Pole Alternator.

In any alternator having p poles there will be $\frac{p}{2}$ complete electrical cycles for each revolution of the shaft, and $\frac{p}{2} \times 360$ electrical degrees will correspond, therefore, to 360 mechanical degrees. For all practical purposes $\pm$ $2\frac{1}{2}$ electrical degrees are equal to 1·4 per cent. of the pole pitch.

(3) The natural period or swing of the combined set shall not approach resonance with any of the disturbing forces of the system.

The cyclic variation is the ratio of the maximum variation in speed during one engine cycle to the mean speed, the usual definition being :—

$$\frac{\text{maximum speed} - \text{minimum speed}}{\text{mean speed}}.$$

Thus, if an engine running at a mean speed of 300 r.p.m. has a maximum speed of 301 r.p.m., and a minimum speed of 298 r.p.m., the cyclic variation is :

$$\frac{301 - 299}{300} = \frac{1}{150}.$$

As an example, one 300 B.H.P., 600 r.p.m., six-cylinder, four-stroke cycle engine, driving a 205 kW., 415 volt, 3-phase, 50-cycle alternator with exciter attached, has a cyclic variation of $\frac{1}{460}$.

If it is assumed that the curve representing speed variation is a sine curve of engine impulse frequency, the cyclic irregularity should not be greater than :—

$$\frac{\text{engine impulses per revolution}}{5{\cdot}7 \times \text{number of alternator poles}}$$

which corresponds to the limit of + or − $2\frac{1}{2}$ electrical degrees.

The cyclic variation of an engine can be calculated, and the method employed is given by C. H. Bradbury (see Bibliography). Since this speed variation is a direct measure of the equivalent voltage variation, absence of flicker is ensured by reducing this variation to a minimum. A figure of $\frac{1}{150} - \frac{1}{250}$ has been found to give satisfactory results. The angular displacement is the maximum allowable displacement either backward or forward from the mean position of rotation. It is usually stated in electrical degrees, 360 of which represent the radial distance between two consecutive like poles. The engine designer requires to know the maximum allowable displacement in mechanical degrees, and, therefore, he divides the figure $2\frac{1}{2}$ by the number of pairs of poles. The maximum figure of $2\frac{1}{2}$ electrical degrees for an angular displacement is specified to ensure that there will be no heavy cross currents flowing between alternators when running in parallel. The magnitudes of both cyclic variation and the angular displacement are directly dependent on the moment of inertia of the flywheel. The engine designer can, therefore, satisfy the first two conditions for parallel running by the correct adjustment of flywheel effect. Both the cyclic variation (irregularity) and angular displacement (deviation) will be considerably magnified if the frequency of the oscillations coincides with, or even approaches, the natural oscillating frequency of the alternator and flywheel, comprising the electro-mechanical system. This condition of hunting due to resonance is only experienced with alternators operating in parallel, and is a function of their capacity to pull each other into synchronism, and of the magnitude of the combined inertias of flywheel and alternator. The danger of running in resonance or of approaching thése conditions can be avoided by providing a flywheel of such an inertia that the natural

oscillating frequency is sufficiently removed from the frequency of any prominent harmonic in the crank effort diagram. Preferably, the natural frequency should be well below that of the lowest harmonic, which has a frequency of one vibration per revolution in the case of steam engines, and also two-stroke cycle engines, and one vibration per two revolutions for four-stroke engines.

Having ensured that the cyclic variation and angular displacement of the engine is such as not to cause trouble, it now remains to be seen whether there will be any dynamic magnification of these disturbances due to the inherent characteristics of the alternator. This dynamic magnification is a form of torsional resonance, and electrically is known as "phase-swinging" or "hunting." For torsional resonance, three factors are essential :—

(*a*) a periodic disturbing force ;

(*b*) a body which is free to vibrate ;

(*c*) an elastic controlling force on the body.

For calculation purposes, alternators in parallel may be likened to shafting systems, the torsional stiffness of the latter being replaced by the "synchronous rigidities" between the machines.

A Diesel-driven alternator with no parallel-running machinery on its system cannot have a natural period, and hence, cannot hunt. With an alternator in parallel, hunting will take place if there is synchronism between the disturbing forces of the engine and the natural period of the alternator. For successful parallel operation, therefore, both these frequencies must be calculated, and one or both must be altered if necessary to obtain as wide a separation as possible between the periods. The engine disturbing frequencies must be known before the natural period can be fixed. The engine disturbing frequencies may be divided into two classes :—

(1) The disturbing torques due to the power impulses of the engine.

(2) A possible variation in speed due to the hunting of the engine governor.

Each cylinder will not always take its correct share of the load, and if this proves to be the case, there will be a periodic wave in the displacement diagram of greater amplitude than its neighbours, and this wave, together with its harmonics, will constitute another set of disturbing forces.

The synchronising of Diesel engines is similar to steam and water turbines. The merits of "lamps bright" or "lamps dark" for synchronising have often been discussed, and both are used in

practice. Both methods appear to have certain advantages and disadvantages. The "lamps bright" method is satisfactory when the neutral of the incoming set is not connected to the neutral of the running sets; but when running up a set to take another off the bus-bars, it is frequently desirable to connect the neutrals before doing so, in order that the earth connection should not be interrupted. In this case, with "lamps bright," the lamps do not reach the maximum intensity simultaneously, and it is difficult to decide the point at which the lamps are of equal brilliance. The "lamps dark" indicates no voltage across the switch of each phase, and no doubt exists. With "lamps bright," synchronising is effected with approximately 60° displacement, whereas with "lamps dark" this is reduced to about 20° angular displacement.

Mechanical shocks, through bad synchronising, can be very severe. If the circuit-breaker is closed before the voltage is exactly in phase, a large current will flow corresponding to the out-of-phase component of the voltage between the bus-bar and incoming alternator. Should this phase difference reach 180° at the instant of switching, conditions are equivalent to a dead short-circuit. Conditions would be more severe than a short-circuit for the incoming alternator, but less severe for alternators already on the bus-bars, because the heavy currents would be distributed among them. The power demand on short-circuit is not uniform, as it is sudden, and alternates between maximum and minimum values throughout each cycle. This surge is reflected to the rotating shaft and tends to twist and untwist it over its length, with possibly serious results.

Synchronising can be simplified by running up engine to synchronous speed with unexcited alternator. The main circuit-breaker is first closed and then field switch. This method of synchronising by "rotor paralleling" causes a switching transient, but is not objectionable. The main circuit-breaker has a no-volt trip coil circuit which is connected to field switch trip (Fig. 632).

In parallel operation, the loads, wattful and wattless, should be shared according to the rated outputs of the sets; the former being indicated on the wattmeter, and the extent of the latter on the ammeter. The watts are determined by the engine power output, and the wattless current by the setting of the exciter rheostat, preferably controlled by an automatic voltage regulator. The voltage regulators should incorporate a compound control coil to ensure equal sharing of the wattless load.

Switchgear and Control Equipment. The main switchgear is usually grouped in the form of a switchboard and placed on the operating floor at the alternator ends of the engines, thus reducing the cabling and keeping it away from the engines. In some cases it is placed in an annexe quite separate from the engine house. A mimic diagram with lamp-type semaphores indicates the position of the circuit-breakers, and also shows whether the bus-bar systems

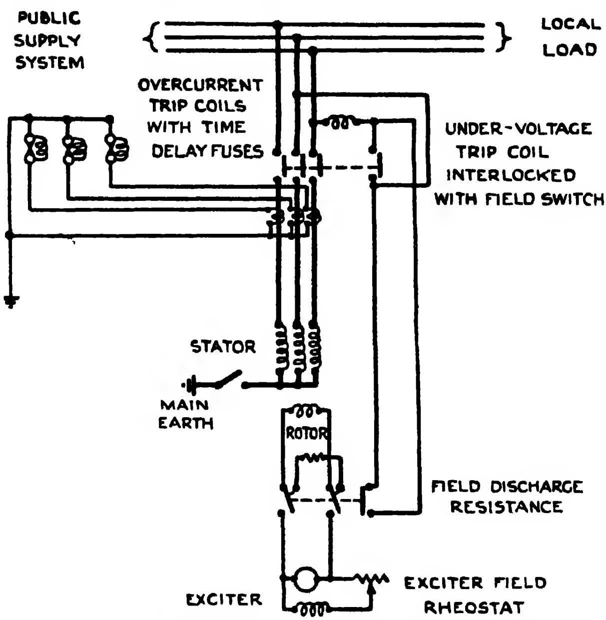

FIG. 632. Paralleling Connections for Diesel-electric Plant.

are alive or dead. Exciter control and neutral earthing cubicles, which accommodate the automatic voltage regulators, can be located adjacent to the alternator control panels. The engine governors can be remote controlled from the main switchboard control panels, making synchronising of the alternators simple and completely under the control of the switchboard attendant. Inter-telephone communication between key points may be included, thus bringing the plant under the control of the shift-charge-engineer.

PLANT OPERATION AND TESTING

Plant Inspection. When carrying out inspections of plant, it is desirable that the engine exhaust should be seen, as the appearance

of the exhaust is sometimes a good indication as to whether the engine is overloaded or not.

Black, smoky exhaust—atomiser.
Black smoke—sign of overloading.
White smoke—running on light load.

The engine should be capable of carrying its full rated output without any undue heating, and indicator diagrams should be taken while under test for the purpose of checking compression, initial pressure, and timing. After completion of the load test, the pistons should be withdrawn for inspection, and the main bearing caps lifted.

The two principal points to be kept in mind when making general inspection of plants are:—safety; and economy and regularity of running. Knocking is the first thing to be noted when plant is running, as this is usually the sign of approaching breakdown. If bedplate is not steady, the foundations, fixing bolts, connections to oil and exhaust pipes, and cooling water system connections should be examined. Heavy back-explosions usually take place when misfiring is prevalent, resulting from charges of gas and air entering the exhaust pipe and being ignited after the next power stroke. Amongst causes of misfiring leading to back-firing are:—loss of compression; choked atomiser; throttled air inlet; defective or sticking valves; insufficient blast air or fuel oil pressure. The satisfactory operation of an engine which is largely dependent on the maintenance of correct compression is fixed by a very fine clearance, wear in main bearings, or in the bearings at either end of the connecting rod. Increasing the clearance will immediately result in loss of compression. Wear on liner or piston rings again will cause loss of compression through leakage, and the same effect will result from piston rings being allowed to become stuck in their grooves with carbon deposit.

If the atomisers are allowed to become clogged and the oil, in consequence, is not completely sprayed, the efficiency of the engine falls off, and the engine rapidly becomes dirty due to the partly unconsumed oil. When the pistons are withdrawn, opportunity should be taken to examine the condition of the liners for wear. It has been suggested that when cylinder wear reaches 80–100/1,000 in. (*i.e.*, 40–50/1,000 wear) down from the top, the liner requires either renewing or reboring. A two-stroke engine with a 12 in. bore would not take the load, and difficulty was experienced

in starting when the liner wear reached $\frac{1}{16}$ in. A new liner and piston were fitted. Condition of pistons, gudgeon pins, and bearings should be noted, the pistons being carefully examined for cracks both on the wearing surfaces and in the internal ribs. Connecting rod bolts and crankshaft can also be examined. Crankshafts which are carried in more than two bearings should be gauged annually for deflection, as it has been found that many crankshaft failures are caused by slight bending of the shaft owing to the bearings being worn or otherwise out of line. Experience shows the need for flooding the bearings of engines with oil before starting, as so many failures seem to occur shortly after the engines are started. Pistons may seize due to faulty lubrication caused by an insufficient supply of oil, or to unsuitable quality. If the latter, an improvement in the conditions may be effected by using an admixture of colloidal graphited oil with the lubricating oil for a month or more, and so restore the bearing surface of the piston and liner.

Fuel Oil. The Diesel engine will run on a wide range of fuels with comparatively little effect upon the primary characteristics of efficiency, measured in terms of power return for B.Th.U.'s expended. Diesel fuels cannot be classified on the basis of performance, and it is rather in respect of secondary characteristics that fuels should be compared. These secondary characteristics may be classified as follows :—cold starting ; Diesel knock ; wear ; fouling, and exhaust smoke. B.S.S. 209—1947 should be referred to for further information.

It is difficult to obtain reliable data relating to the various fuels used in different plants ; the following relates to Bunker-C fuel :—

Specific gravity at 68° F.	0·98
Flashpoint, °F.	230
Viscosity at 122° F.	200
,, ,, 212° F.	160
Carbon, per cent.	11
Sulphur ,, ,,	32
Hard asphaltum	Nil
Calorific value, B.Th.U./lb.	18,500

This fuel is heated to about 210° F. to obtain the desired viscosity of 125 to 175 at the fuel injection.

Plant Performance. The average fuel consumption, based on a large variety of plants of different outputs, appears to be about 0 6 lb. per kWh. generated with a running load factor of about

65 per cent. Lubricating oil consumption based on the rated B.H.P. hour run per gallon varies between 2,400 to 9,900, whereas the arbitrary standard is reckoned at 2,380. The ratio of fuel to lubricating oil consumed varies from 100 to 260.

Fig. 633 gives typical plant performance data for one large installation.

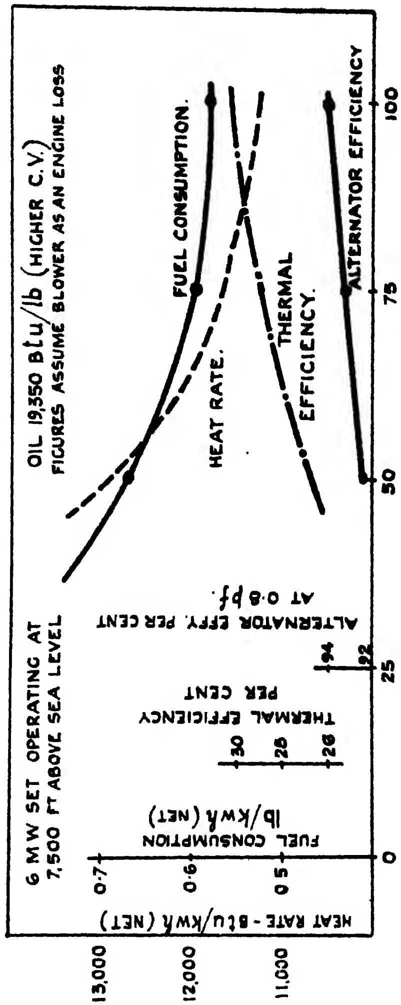

Fig. 633. Plant Performance Data.

The heat balance sheet can be drawn up for any engine, provided certain data are available, viz.:—

(1) Heat supplied per I.H.P. per hour = lb. fuel per I.H.P. per hour $\times$ calorific value.

(2) Heat converted to work per I.H.P. per I.H.P. hour

$$\frac{1 \text{ I.H.P.} \times 33{,}000 \times 60}{J}$$

where J = 778 B.Th.U.'s, or 1,400 C.H.U.'s.

(3) Heat lost in cooling water = lb. water per I.H.P. hour $\times$ specific heat $\times$ temperature rise.

(4) Heat lost in exhaust = lb. gas per I.H.P. hour $\times$ specific heat $\times$ temperature rise.

$$\text{Actual air supplied per lb. of fuel} = \frac{\text{N.C.}}{33(CO_2 + CO)}$$

Weight of exhaust gases = weight of air + contents of 1 lb. of fuel.

(5) Unaccounted for, radiation, etc. (by difference).

Heat balance sheet can then be drawn up as follows :—

Item	B.Th.U.'s or C.H.U.'s	Per cent.
(1) Heat supplied per I.H.P. per hour .		100
(2) Heat converted to work per I.H.P. per hour		
(3) Heat lost in cooling water . . .		
(4) Heat lost in exhaust gases . . .		
(5) Unaccounted for (by difference) . .		

The following examples indicate the solution of a number of typical problems.

Example. Analysis by weight of crude petroleum gave :—

Carbon 85 ; Hydrogen 13·5 ; Incombustible matter 1·5.

Volumetric analysis (per cent.) of exhaust gases gave :—

CO_2 7 ; Oxygen 11·3 ; Nitrogen 81·7.

The engine uses 0·33 lb. of oil per I.H.P. per hour, and 14·8 lb. of water per I.H.P. per hour pass through the jacket. The rise in temperature of the jacket water is 52° C., temperature of exhaust 384° C., lower calorific value of the oil is 10,720 C.H.U.'s per lb., and specific heat of the exhaust gases is 0·24.

Draw up a heat balance sheet for the engine.

(1) Heat supplied per I.H.P. per hour

$$= 0{\cdot}33 \,.\, 10{,}720$$
$$= 3{,}540 \text{ C.H.U.'s.}$$

(2) Heat converted to work per I.H.P. per hour

$$= \frac{1 \,.\, 33{,}000 \,.\, 60}{1{,}400}$$
$$= 1{,}410 \text{ C.H.U.'s.}$$

(3) Heat lost in cooling water $= 14{\cdot}8 \,.\, 1 \,.\, 52$

$$= 770 \text{ C.H.U.'s.}$$

Actual air supplied per lb. of fuel

$$= \frac{N \,.\, C}{33(CO_2 + CO)}$$
$$\frac{81{\cdot}7 \,.\, 85}{33 \,.\, 7} = 30 \text{ lb.}$$

Weight of exhaust gases = weight of air + 1 lb. of fuel
= 30 + (0·85 + 0·135)
= 31 lb. approx.

∴ Weight of exhaust gases per I.H.P. per hour
= 0·33 . 31
= 10·23 lb.

(4) Heat lost in exhaust gases = 10·23 . 0·24 . 384
= 945 C.H.U.'s.

(5) Losses unaccounted for = 3,540 − (1,410 + 770 + 945)
= 415 C.H.U.'s.

HEAT BALANCE SHEET

	C.H.U.'s	Per cent.
(1) Heat supplied	3,540	100·0
(2) Heat converted to work . . .	1,410	39·8
(3) Loss to cooling water . . .	770	21·7
(4) Loss to exhaust gases . . .	945	26·7
(5) Loss unaccounted for . . .	415	11·8

Example. An oil engine having a compression ratio of 4·7, consumes 1·18 lb. of oil per I.H.P. hour. If the oil has a calorific value 10,000 C.H.U.'s per lb., find the efficiency of the engine and also its efficiency ratio to that of Standard Otto cycle.

$$\text{Output per I.H.P. hour} = \frac{1 \,.\, 33{,}000 \,.\, 60}{1{,}400} = 1{,}410 \text{ C.H.U.'s.}$$

$$\text{Input per I.H.P. hour} = 1{\cdot}18 \,.\, 10{,}000 = 11{,}800 \text{ C.H.U.'s.}$$

$$\therefore \text{Efficiency} = \frac{1{,}410 \,.\, 100}{11{,}800} = 12 \text{ per cent.}$$

$$\text{Efficiency ratio or relative efficiency} = \frac{\text{actual efficiency}}{\text{air standard efficiency.}}$$

$$= \frac{E_A}{1 - \left(\frac{1}{r}\right)^{\gamma-1}} = \frac{0{\cdot}12}{1 - \left(\frac{1}{4{\cdot}7}\right)^{1.4-1}}$$

$$\log 0{\cdot}213 = \bar{1}{\cdot}3283$$
$$0{\cdot}4$$
$$\overline{\qquad\qquad}$$
$$0{\cdot}13132$$

$$= \frac{0{\cdot}12 \,.\, 100}{1 - 0{\cdot}538} = 26 \text{ per cent}$$

$$-0{\cdot}4 = \bar{1} + 0{\cdot}6$$

$$\begin{array}{r} 0{\cdot}13132 \\ 0{\cdot}60000 \\ \hline 0{\cdot}7313 \\ \hline \end{array}$$

antilog $0{\cdot}7313 = 0{\cdot}538$.

Constant volume cycle :—

$$\text{let } r = \frac{\text{maximum volume V1}}{\text{minimum volume V2}} = \text{compression ratio.}$$

Thermal efficiency $= 1 - \left(\frac{1}{r}\right)^{\gamma-1}$. The efficiency of the constant volume cycle depends upon the compression ratio alone.

Diesel cycle :—

Starting with air at maximum volume V1 (Fig. 634).

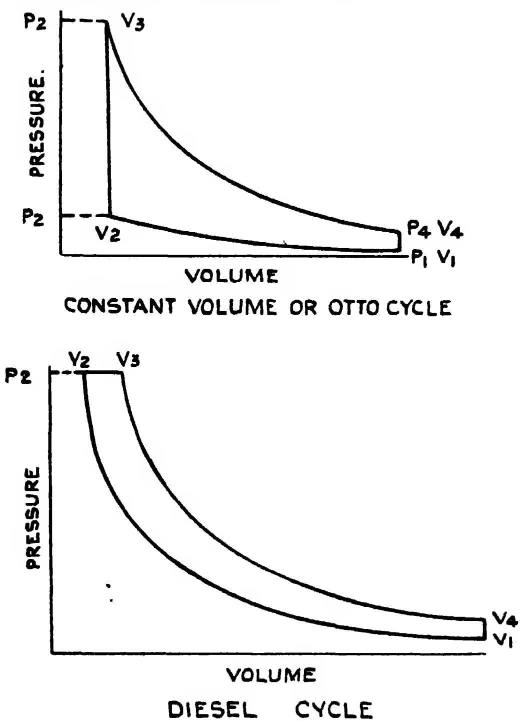

Fig. 634. Cycle Diagrams.

(1) Adiabatic compression from V1 to V2, raising the pressure to P2.
(2) Heat supplied at constant pressure P2 from volume V2 to V3.
(3) Adiabatic expansion from V3 to V4.
(4) Rejection of heat at constant volume V4.

$$\text{Let } x = \frac{\text{volume at cut off}}{\text{volume of clearance space}} = \frac{V3}{V2}$$

$$\text{Thermal efficiency} = 1 - \left(\frac{1}{r}\right)^{\gamma-1} \times \left\{\frac{x^{\gamma} - 1}{\gamma\,(x - 1)}\right\}$$

This efficiency, given equal values for the compression ratio, is less than that of the constant volume cycle. For true adiabatic compression and expansion the index will be equal to "γ" the ratio of the specific heats.

Example. Test on four-stroke cycle engine: duration of trial 14 minutes; oil used 12·9 lb.; total revolutions 8,142; jacket water 738 lb.; temperature rise of jacket water 74° F.; mean effective pressure 96 p.s.i.; torque due to brake load 786 lb. ft.; lower calorific value of oil 17,000 B.Th.U.'s per lb.; piston area 112 sq. in.; stroke $18\frac{1}{4}$ in.

$$\text{I.H.P.} = \frac{\text{PLAN}}{33{,}000} \qquad \text{N} = \frac{\text{N}}{2} \text{ for four-stroke engine.}$$

$$\text{N} = \frac{8{,}142}{14\ .\ 2} = 290$$

$$= \frac{96\ .\ 18{\cdot}25\ .\ 113\ .\ 290}{12\ .\ 33{,}000} = 145.$$

$$\text{B.H.P.} = \frac{2\pi\ .\ \text{N}\ .\ \text{T}}{33{,}000} = \frac{2\pi\ .\ 580\ .\ 786}{33{,}000} = 86{\cdot}5$$

Oil consumed per I.H.P. hour $= \dfrac{12{\cdot}9\ .\ 60}{145\ .\ 14} = 0{\cdot}38$ lb.

Oil consumed per B.H.P. hour $= \dfrac{12{\cdot}9\ .\ 60}{86{\cdot}5\ .\ 14} = 0{\cdot}65$ lb.

Heat supplied per minute $= \dfrac{12{\cdot}9\ .\ 17{,}000}{14} = 15{,}700$ B.Th.U.'s.

Heat converted to work per minute $= \dfrac{145\ .\ 33{,}000}{778} = 6{,}150$,,

Heat rejected by jacket per minute $= \dfrac{738\ .\ 74{\cdot}1}{14} = 3{,}900$,,

Heat unaccounted for per minute (radiation, exhaust gases) $= 15{,}700 - (6{,}150 + 3{,}900) =$ 5,650 B.Th.U.'s.

The Heat Engine Trials Committee of the Institution of Civil Engineers, in their report, give the thermal efficiency as $= \dfrac{100 \,.\, \text{B.H.P.} \,.\, 2{,}546}{\text{Gross calorific value} \times \text{fuel lb./hr.}}$. This Committee also adopted the higher (or gross) calorific value of the fuel as the figure to be used in all calculations, as this is a figure obtained by direct experiment.

Staffing. The personnel employed will depend chiefly on the capacity of plant installed, and the usual requirements are :—station or resident engineer ; shift charge engineers ; switchboard attendants, drivers, and auxiliary plant attendants, and a number of clerks and manual workers.

COSTS

Diesel engine plants are generally only used for isolated stations of comparatively small outputs, except in those countries where fuel-oil is a local product.

Before the advent of the National "Grid" system in this country, there were numerous Diesel-engine stations, all of which served a useful purpose in affording a supply to isolated and scattered communities. Many have been closed down, but some were retained as peak-load stations and operate on a one or two-shift basis.

It is difficult to obtain reliable information relating to capital and operating costs which would serve to compare one plant with another, as so many variable factors have to be taken into consideration. These stations can be commenced on a small scale and extended with but little trouble, particularly if the same types of plant are installed.

The capital cost per kW. of plant installed (engine, alternator and exciter) is considerably higher than that of equivalent steam-turbine plant and decreases as the outputs of the sets are increased ; £25 to £30 per kW. for sets up to about 500 kW. and from £20 to £25 per kW. for larger sets. During the year 1949 some ten sets, each 940 kW., were ordered for East Africa, and the average cost was £32 per kW. A 7 MW plant was estimated to cost £281,000 (1950).

The renewals and replacement costs are influenced by many factors, such as :—load factor, number of cold starts per 1,000 hours, type of cooling system, running clearance, class of fuel and lubricating oil. All of these affect the wear and life of the various working parts of the plant. Some typical figures for renewals and replacement costs are as follows :—

Annual Load Factor Per cent.	£ per Annum per Average kW. installed
40	1·00
30	0·62
20	0·35
10	0·15

Examples of small Diesel engine-alternator stations are given, and the costs relate to the years 1944–45 and 1946–47 :—

(1) Plant installed : 2—450 kW. sets, 4—305 „ „ } 2·12 MW.

	£
Fuel oil cost	6,700
Lubricating oil, waste, water, etc.	350
Wages	490
Repairs and maintenance	1,000
Total operating cost	£8,540

Units generated per annum	2,220,000
Cost per unit generated	0·923 pence

(2) Plant installed : 6—307 kW. sets, 6·6 kV. (1·84 MW).

Total generation costs	£14,890
Maximum load	1·67 MW
Units generated	4,298,760

Station load factor $= \dfrac{4{,}298{,}760 \cdot 100}{1{,}670 \cdot 8{,}760}$

$= 29{\cdot}3$ per cent.

Average fuel consumption 0·526 lb. per unit generated
Approximate thermal efficiency . 32 per cent.

Cost per unit generated . $= \dfrac{14{,}890 \cdot 240}{4{\cdot}298 \cdot 10^6} = 0{\cdot}84$ pence

(3) Plant installed : 3—400 kW. sets, 1—600 kW. set, 1—800 ,, ,, 1—900 ,, ,, (3.5 MW) 6·6 kV.

Units generated	4,076,910
Maximum load	2·88MW
Generation costs :	£
Fuel oil	5,000
Wages	3,000
Maintenance	2,660
Total	£10,660

$$\text{Cost per unit generated} = \frac{10{,}660 \,.\, 240}{4{\cdot}076 \,.\, 10^6} = 0{\cdot}63 \text{ pence}$$

$$\text{Station load factor} = \frac{4{\cdot}076 \,.\, 10^6 \,.\, 100}{2{,}880 \,.\, 8{,}760} = 16 \text{ per cent.}$$

(4) Plant installed : 2—450 kW., D.C., 460-v. 4—305 ,, A.C., 11 and 6·6 kV. 2·12 MW.

Units generated	2,778,726
Units sent out	2,687,474
Units used in station . . .	91,252
Maximum load sent out . . .	2·22 MW
,, ,, on plant . . .	2·30 ,,
Generation costs :	£
Fuel oil	5,966
Oil, waste, etc.	518
Wages	857
Repairs and maintenance . .	1,376
Total	£8,717

$$\text{Cost per unit generated} = \frac{8{,}717 \,.\, 240}{2{\cdot}778 \,.\, 10^6 \,.\, 8{,}760} = 0{\cdot}86 \text{ pence}$$

$$\text{Station load factor} = \frac{2{\cdot}778 \,.\, 10^6 \,.\, 100}{2{,}300 \,.\, 8{,}760} = 13{\cdot}8 \text{ per cent.}$$

$$\text{Station auxiliaries} = \frac{91{,}250 \,.\, 100}{2{\cdot}778 \,.\, 10^6} = 3{\cdot}3 \text{ per cent.}$$

Average fuel consumption . 0·6 lb. per unit generated
Approximate thermal efficiency . 29·2 per cent.

(5) Plant installed : 5—350 kW. sets (A.C.) } (2·91 MW)
4—290 „ „ (D.C.) }

Units generated	1,540,060
Units sent out	1,368,620
Units used in station . . .	171,440
Maximum load on plant . .	1·7 MW
Generation costs	£10,860

$$\text{Cost per unit generated} = \frac{10{,}860 \cdot 240}{1{\cdot}54 \cdot 10^6 \cdot 8{,}760} = 1{\cdot}94 \text{ pence}$$

$$\text{Station load factor} = \frac{1{\cdot}54 \cdot 10^6 \cdot 100}{1{,}700 \cdot 8{,}760} = 10{\cdot}3 \text{ per cent.}$$

Average fuel consumption . 0·675 lb. per unit generated
Approximate thermal efficiency . . 24·6 per cent.

$$\text{Station auxiliaries} = \frac{171{,}440 \cdot 100}{1{,}540{,}060} = 11 \text{ per cent.}$$

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CHAPTER XXVI

GAS TURBINE PLANTS

It was inevitable that the success which has attended the steam turbine should turn the minds of engineers towards the problem of designing and constructing a turbine which will utilise in a similar manner the heat generated by the combustion of gaseous or liquid fuels.

The thermal conditions of the steam and gas turbine are far apart, while the mechanical considerations are also widely different. These are primarily due to the different components which are necessary as the result of the differences in the cycles of operation, and also the difference of the maximum temperatures to which the materials of the respective systems are subjected.

The gas turbine, after it has been demonstrated as a practical working machine for electric power production, will have to justify itself in respect of capital and running costs.

As happened earlier with steam, a change from reciprocating to rotary motion represented a new stage. The overall efficiency of the gas turbine as a prime mover is limited by the fact that a large proportion of the power produced is required to drive the compressor and also by the temperatures safely attainable.

In the new application of the jet propulsion principle to aeroplane propulsion, all the output is absorbed by the compressor and the energy assumes a different form.

In principle, a turbo-compressor compresses pure air or air and gas to a high compression, then combustion takes place at a constant pressure, and the products of combustion expand down to atmospheric pressure in the working turbine.

The gas turbine as a prime mover was proposed over 150 years ago, but the earliest gas turbine of which there appears to be a published record was built about 1900. The first patent for a gas turbine was granted in 1791 in England to John Barber, whose proposals were very close to modern principles and included the injection of water into the combustion chamber to cool the products of combustion and augment their volume.

In 1861 a patent was granted to M. A. F. Mennons for an open-cycle gas turbine which operated with solid fuel, and incorporated

all the principal components of a modern open-cycle unit, including a regenerator.

C. G. Curtis took out a patent in the U.S.A., in 1895, for an open-cycle gas turbine, using solid, liquid or gaseous fuel.

In spite of this early theoretical work, little success was achieved in the practical development of the gas turbine. There were two principal causes for this delay, namely, the difficulty in obtaining materials which would stand up to the high temperatures, and the low efficiencies of both compressors and turbines. As a result, the compressors absorbed more power than was developed by the turbine, and therefore power would have had to be supplied to the unit to enable it to run at all.

Early developments were handicapped by lack of aerodynamic data which resulted in compressors of low efficiency, and by lack of high temperature materials, which restricted maximum operating temperatures. At various stages of development many proposals have been put forward to employ gas turbines with reciprocating engines, with steam turbines, or a combination of both.

The first gas turbine for public electricity supply was ordered in 1938 and installed in 1940, and comprised a 4 MW set for an underground bombproof station at Neuchatel, Switzerland.

Gas turbines for aircraft propulsion have made considerable progress, and is really the only field of application in which there is extensive operating experience. The aero-engine is of light weight, has a very high rating, and the life is short. Much experience of very high temperatures, working stresses, aerodynamics of compressors, combustion systems and materials, has been gained in this field, which has expedited progress in gas turbines for power plant service.

The first gas turbine locomotive was commissioned in 1941, and the first gas turbine driven ship in 1947.

During recent years a number of gas turbine plants have been ordered, and some commissioned for public electricity supply systems. The majority of these plants are either for peak load service or for stand-by in hydro-electric power plants. The others have been provided for base load requirements in countries where oil or natural gas fuel are cheap. Gas turbine plants of sufficient capacity to create the necessary proportion of firm power to make tidal power schemes economic might be possible when more operating experience and larger and cheaper units are available for use with electrolytic hydrogen, blast-furnace gas or pulverised coal. The

ability to start up and shut down rapidly and to deal with varying loads are essential characteristics for parallel operation with a tidal power station.

An important feature under Swiss conditions is that in winter, when the electrical demand is greatest, much of the rain-water is locked up in glaciers to be released in spring into lake reservoirs. Should warm weather be unduly delayed in the year, the water in the reservoirs may easily fall to a dangerously low level, so a reserve of perhaps as much as one-third of the water has to be retained. The availability of gas turbines for continuous operation obviates this necessity.

Changes in the shape of the daily and annual load curves and increase in load factor have resulted in a spreading of the " peaks " over several hours of the day, on top of which there are periodic short peaks which may in some cases have to be shed due to the shortage of generating plant. The growing need to meet peak loads with plant of relatively low capital cost which can be quickly put into commission, and which occupies little space, gives the gas turbine immediate value, while expectations of improvements in thermal efficiencies and other economies make its development desirable.

Although there have been rapid advances in the development of the gas turbine, it seems unlikely that it will become a serious competitor of the steam turbine for large outputs. In a way it is more of a threat to the large Diesel engine, while being also well-suited to certain requirements or conditions, such as emergency stand-by generation duty, where water supply is absent or when coal is expensive and gas or oil fuel cheap.

For really large outputs, the advantages of initial cost, fuel consumption and space economy, combined with high efficiency of the steam turbine, leave it almost unchallenged.

Recent progress in metallurgy is such that metals are available which are capable of standing up for economic periods to the high temperatures required to obtain efficiencies comparable with those in steam practice.

The use of gas turbines is not dependent on the availability of large water supplies as are other internal combustion engines and steam turbines.

There is also the possibility of converting coal into producer gas and supplying it to gas turbines. In these circumstances where the majority of the heat in the turbine exhaust can be profitably

used for district heating or low-pressure steam turbines, the gas-burning internal combustion turbine promises a considerable reduction of generating costs below those of equivalent steam-turbine plant, while offering further advantages in such directions as cheaper sites and buildings for power stations. The gas cycle is inherently capable of giving higher thermodynamic efficiencies than the steam cycle and affords the further advantages of eliminating boilers and condensing plant.

In the very early experimental plants the net power made available was exceedingly low since the gross output was absorbed in compressing the gas. Alloy materials are now available which can withstand the higher temperatures necessary to secure reasonably good turbine performance. Further, advances in compressor design have enabled rotary compressors to deal efficiently with large volumes of gas.

The principal requirements of prime movers for general purposes are long life, high efficiency and reliability in continuous service, whereas minimum weight, among other factors, are essential for aircraft.

In 1934 the Sun Oil Company, America, took an interest in the Houdry oil cracking process, which requires large quantities of compressed air for burning off the catalyst. In conjunction with this process Messrs. Brown Boveri supplied gas turbines similar to those which had been used for the Velox boiler installations. They were primarily used as auxiliaries and produced a surplus of power. The plant was tested at the makers' works before despatch by burning oil in a cylindrical combustion station. An enlargement of the Houdry machine actually became the first turbine to fulfil expectations in commercial service.

A 13 MW set was put into service at Beznan in Switzerland in December, 1947, and a further 27 MW set was under construction. Erection of the first set commenced one year from the date of order, and it was running within eighteen months. A similar set for Rumania operates on natural gas, and has been run up and put on to full load within seven minutes.

With its comparative freedom from cooling water requirements and an efficiency comparable with that of a good steam plant, coupled with its moderate first cost, and its low maintenance figures, the gas turbine in the particular field of blast-furnace blowing (using either blast-furnace gas or coke oven gas as fuel) may become an attractive proposition.

The development of the gas turbine for power plants has been retarded by the existence of certain technical problems, but these are being gradually surmounted. Gas turbines are only likely to be used for electric power production where oil fuel is cheap, water scarce, natural gas available, or where the load factor is low. Standardisation of components should ultimately help to cheapen and simplify gas turbine applications.

Research work is still progressing, and such basic problems as air flow, combustion, behaviour of materials at high temperatures, stresses in components, vibration, and methods of manufacture are being tackled.

Thermal efficiencies of 40 per cent. and over are regarded as being practicable, and although work is not at present being attempted with pulverised fuel, it is considered that, providing some means of eliminating deposits on the blades can be devised, there should not be very much difficulty in utilising this form of fuel.

CONSIDERATIONS AFFECTING CHOICE OF PLANT

At the present stage of development it is rather difficult to lay down any hard and fast rules concerning the choice of gas turbines for a power plant service, but generally speaking some of the following factors will have to be reckoned with when contemplating the installation of such prime movers :—

(1) The capital cost of a gas turbine plant is lower than that of a comparable steam plant.

(2) The efficiency is about the same.

(3) The gas turbine plant has no stand-by losses and can be started and put on full load more quickly.

(4) A smaller site area is required for a gas turbine plant, and can be adapted to existing steam and hydro-electric power plants. Almost twice as much gas turbine capacity as steam plant capacity can be installed on a small site. High space utilisation.

(5) The plant can be readily located in cities and industrial centres in close proximity to areas of heavy electrical demand.

(6) Short running hours is a condition favourable to gas turbines.

(7) Fewer auxiliaries are required and control of the turbine is very simple. A separate small Diesel-driven alternator serves to supply starting motor.

(8) Foundations and buildings are less costly.

(9) No high pressure piping and minimum water requirement.

For operating conditions below a given load factor, the gas turbine becomes an economic proposition as the saving on capital charges outweighs the additional cost of fuel. Conditions are especially favourable to the gas turbine on existing sites for the replacement of obsolete steam turbine plant.

Gas turbine plants are also well suited for stations which, in the absence of these plants, would have had oil or gas burning steam plant installed.

In general, gas turbines can be built relatively quickly, and require much less space and civil engineering work and water supplies ; they can be run up from cold and put on load in a few minutes and require less attendance. A further advantage is that the components and circuits can be varied to give the most economic results in any given circumstances.

Load factors of from 15 to 18 per cent. appear to offer the most economic range. It has been said that the future of the gas turbine depends principally on its ability to use waste heat. Constructional advantages associated with the gas turbine are the elimination of boilers and condensing plant.

It is doubtful whether it is worth while building more than a few of these plants in this country owing to the cost of fuel. At present it is only when the open cycle gas turbine is restricted to loads with completely uneconomic load factors that its fuel costs will not bring the total cost of production above that of the steam turbine. Although the same argument did not necessarily apply to the closed-cycle plant, this is complicated, and its capital cost is at least equal to that of steam plant.

For base load power stations, much depends on what use can be made of its waste heat, and the combination of gas turbine, gas producer and district heating may quite well prove successful.

Producer gas is usually made by passing superheated steam through an incandescent bed of fuel and the valuable by-products can be extracted. If the development of the gas turbine proceeds satisfactorily such plants may come into more general use.

Should the production of electrical power ultimately be founded on the use of nuclear energy, the gas turbine will no doubt provide the most suitable means of converting the heat energy of the pile into power.

CHOICE OF CYCLE

The many cycles available is to a certain extent due to the need for a gas turbine plant to approximate to an equivalent steam turbine plant. The following factors will require consideration when choosing a cycle for any specific installation :—

(1) The components on any particular shaft must satisfy a power balance themselves.

(2) Compression and expansion should be so split up as to give maximum benefit from intercooling and reheat.

(3) The components should be so disposed as to improve on the very poor part load of the simple cycle.

(4) Space considerations and mechanical stress limitations may make it necessary to modify the layout.

There is a wide range of choice of cycle conditions, which are dependent upon the operating cycle employed. The choice is largely governed by considerations of overall economy to meet any particular requirements. The regenerative cycle can be made more efficient by adding reheat between the high pressure and low pressure cylinders with a separate combustion chamber to put heat back into the gases exhausted from the high pressure cylinder before entering the low pressure. By including intercooling to regeneration an efficiency approaching 40 per cent. is attainable.

Capital cost, fuel cost, maintenance and running costs, together with plant availability, all require careful investigation.

The higher the maximum temperature of the working medium in a given cycle, the higher is the thermal efficiency and the greater the output for a given plant.

The upper limits of temperature vary according to the type of plant, but the following figures are typical of present-day plants :—

Base load plant	1,050–1,200 °F.
Peak ,, ,, ...	1,100–1,300 °F.

The pronounced effect of temperature on the thermal efficiency can be seen from Fig. 635 for a simple open-cycle plant with compressor and turbine efficiencies of 85 and 90 per cent. respectively.

There is usually one component which is most critical to maximum temperature owing to the combination of mechanical stress and temperature conditions in the materials of this component. In an open-cycle plant, the first stage moving blades of the turbine is affected whereas in a closed or partly closed-cycle a part of the air

heater may be subjected to a temperature higher than the maximum temperature of the working medium.

A reduction of lower temperature limit in the cycle is beneficial both for thermal efficiency and for output from a given plant.

With an open-cycle plant, the lower temperature is fixed by atmospheric temperature, and some Swiss hydro-electric stand-by plants are sited to take advantage of low atmospheric temperature. For closed-cycle plant, and for open-cycle plant when intercooling is used, the lower temperature limit is determined by the cooling water and the air cooler design.

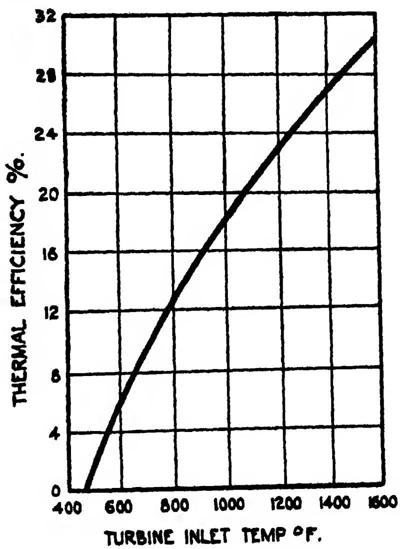

FIG. 635. Effect of Temperature on Thermal Efficiency.

The performance of a plant in service is affected by variation in atmospheric conditions. With a simple open-cycle plant the maximum output, so far as it is controlled by gas conditions in the cycle, diminishes with rising atmospheric pressure. Some cycles are little affected by normal variations in atmospheric pressure. With a closed-cycle plant, the maximum output is not affected by barometric pressure, but is sensitive to cooling water temperature. Either cycle may be utilised for single or two-stage plants, with intermediate heating, and with inter-stage cooling in the compression cycle.

The Carnot cycle-isothermal compression, adiabatic compression, isothermal expansion, adiabatic expansion—represents the ideal process for thermal prime movers, from the standpoint of thermal efficiency. The practical application, however, presents considerable drawbacks in respect of the utilisation of air and other gases.

To attain the high initial temperatures which the use of present-day steels permits, necessitates very high maximum-to-minimum pressure ratios, of the order of 200 to 300. These are difficult to realise in turbo-machines.

Open-cycle Plant. The open-cycle gas turbine of the combustion type consists of a unit comprising an axial flow compressor, a relatively small combustion element and a turbine resembling a reaction non-condensing turbine. Products of combustion are expanded in the turbine and exhausted to atmosphere. The chemical energy of the fuel is converted into heat energy by being burned with sufficient excess air (600 per cent. when turbine inlet temperature is 1,200° F.) to obtain the desired temperature, instead of being converted, as in the steam cycle, into another medium at a lower temperature before expansion. Higher thermo-dynamic efficiencies are therefore theoretically possible than with steam.

In the simple open-cycle (Fig. 636) air is aspirated from the

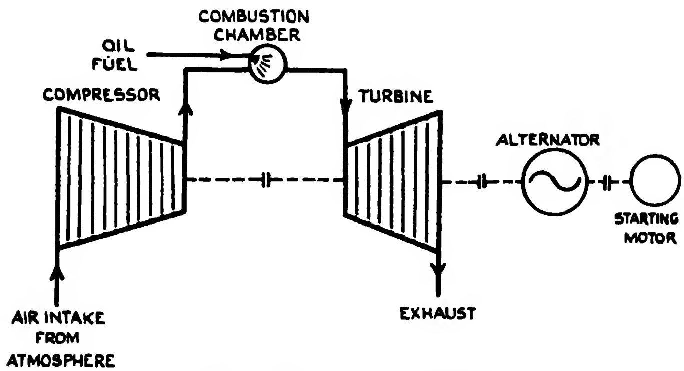

FIG. 636. Simple Open-cycle Plant.

atmosphere, compressed in an axial flow compressor, and passed to the combustion chamber in which fuel is burnt along with the compressed air ; the products of combustion then expand through the turbine and are finally exhausted to the atmosphere. Its essential features are :—

(1) An air compressor which compresses the air to a pressure of three or four atmospheres.

(2) A combustion chamber where fuel is fired and the air raised to a high temperature at constant pressure.

(3) A turbine where the gas is expanded down to approximately atmospheric pressure.

The thermal efficiency of a turbine working on this simple cycle is low, and varies greatly with the temperatures adopted and with the efficiencies of the turbine and compressor. With present-day materials the thermal efficiency is about 16 to 23 per cent.

Due to the high temperature of the products of combustion, the turbine output exceeds the input to the compressor, and the turbine therefore drives the compressor and the surplus power available drives the alternator.

Another arrangement (Fig. 637) has a separate low-pressure power turbine operating in series with the high-pressure turbine.

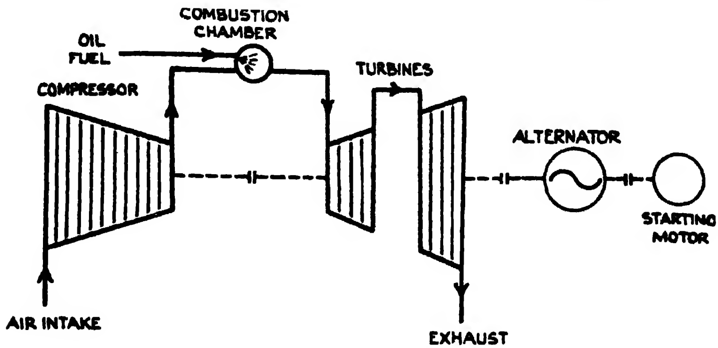

FIG. 637. Open-cycle Plant with Separate Power Turbine

This arrangement permits of speed variation of the compressor while the turbine is synchronised, and this affords improved partial load performance.

Fig. 638 shows the simplest possible type of open-cycle plant for external combustion, in which the compressed air is heated in an

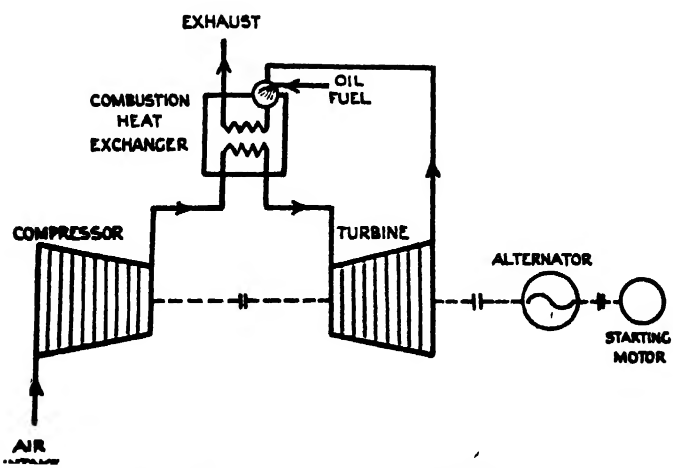

FIG. 638. Open-cycle Plant with External Combustion.

exchanger. Combustion takes place on the other side of the exchanger using the exhaust air from the turbine. In Fig. 639 air is taken in through the compressor, passes through the heat exchanger to the combustion chamber, does work in the turbine and is discharged to the atmosphere *viâ* the other side of the exchanger. The latter equipment is not essential to the principle but is necessary from the point of view of efficiency.

Open-cycle plants occupy comparatively little space, require a small amount of water, and can be quickly run up from cold. Component or auxiliary refinements can usually be varied to improve the thermal efficiency and give the most economical overall cost for the plant load factors and other operating conditions envisaged.

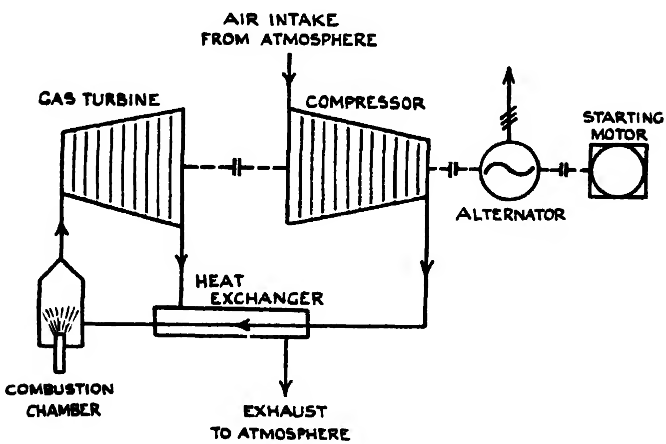

FIG. 639. Open-cycle Plant with Regenerator.

The stipulation of a quick start and take-up of load frequently determines the choice of the open-cycle design.

A recent 15 MW open-cycle oil-fired gas turbine was selected because its thermal efficiency was expected to be equal to that of the most efficient steam set. Further, having regard to the cost of oil, it will be mainly used for peak loads for which its quick-starting characteristics make it especially suitable. Another advantage in its favour was its compactness, as the site was very restricted.

Since it requires no condensing cooling water, the simple open-cycle plant can be used where supplies of water are not available.

The large blade dimensions limit the net output of the open-

cycle, single flow combustion gas turbine, although the injection of liquids is considered a possibility and will extend the present limit.

It is essential that dust should be prevented from gaining access to the system in order to minimise erosion and deposition on the blades and passages of the compressor and turbine, and so impairing their profile and efficiency. Air filters can be included to overcome this difficulty.

Fig. 640 shows a plant with intercooling, reheating and regeneration.

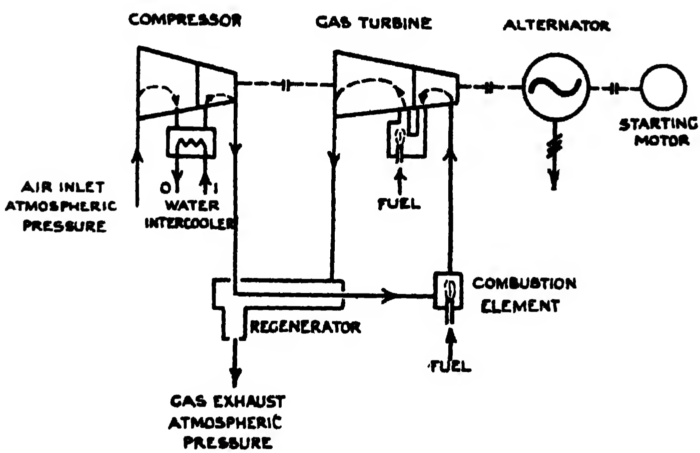

FIG. 640. Open-cycle Plant with Intercooling, Reheating and Regeneration.

Closed-cycle Plant. In this cycle (Figs. 641, 642 and 643) the working medium, air, is continuously circulated through the compressor, heat exchanger, air heater, turbine, heat exchanger and air cooler. Combustion air is drawn from and exhausted to atmosphere through an air pre-heater for reasons of efficiency. The heat supply from outside is provided by combustion in the air heater, and the heat is removed at the low temperature level by the cooling water to the air cooler.

Load variation is usually obtained by varying the absolute pressure and the mass flow of the circulating air, while the pressure ratios, the temperatures, and the air velocities remain almost constant. With the running line at a fixed speed this results in velocity ratios in the compressor and turbine remaining independent of the load, and full load thermal efficiency is maintained at partial loads.

Advantages are claimed from isolation of the working medium within a closed-circuit and its continuous recirculation. High efficiency is maintained over the full range of operating loads with practical freedom from deterioration of efficiency in service. Some of the advantages claimed include the absence of risk of corrosion and abrasion of the interiors of the turbine and compressor, since they are kept free from the products of combustion. This permits the use at present of bunker oil, and as a later possibility, of pulverised coal as a means of securing the requisite high temperatures. Working temperatures are the same at all loads, variations in which are met by a proportionate change of air density.

The maximum unit capacity can be increased by adopting a closed-cycle in which the gas is at a relatively high pressure, thus

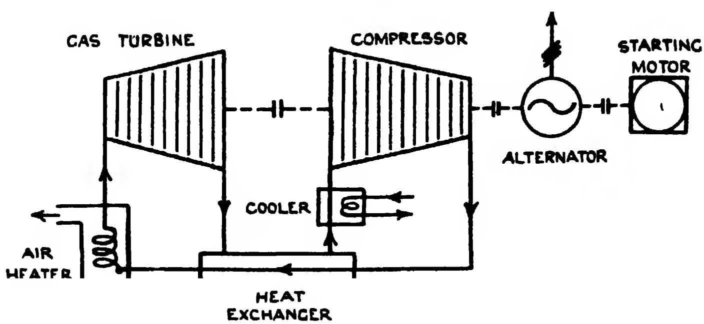

FIG. 641. Closed-cycle Plant.

enabling the physical dimensions of turbine and compressor to be reduced and making possible an approach to standard steam turbine ratings.

Gas is cooled before entering the compressor, and the amount of heat given up to the cooling water is equivalent to that removed in the condenser of a similar steam unit. The quantity of cooling water required is less as a high temperature rise is permissible.

Further possibilities include the use of working medium other than air and with still higher efficiencies. The closed-cycle, by ensuring a clean working media, eliminates fouling and loss of operating efficiency from that cause. Since the specific volume of the working medium is small, because of the relatively high internal pressure, compressors and turbines are small for their rated output. Certain constructional advantages result from this and the absence of any regulating valves.

For a 12 MW, 600 p.s.i. plant, the maximum diameters of the various units would be approximately as follows :—

H.P. turbine . .	20 in.
L.P. ,, . .	40 ,,
L.P. axial compressor	12 ,,
L.P. ,, ..	30 ,,

Despite the high temperatures in use, the extent to which special heat-resisting steels are required is but small. By employing a double-shell construction for piping and turbine casing, the inner high temperature parts can be relieved of high pressure strain.

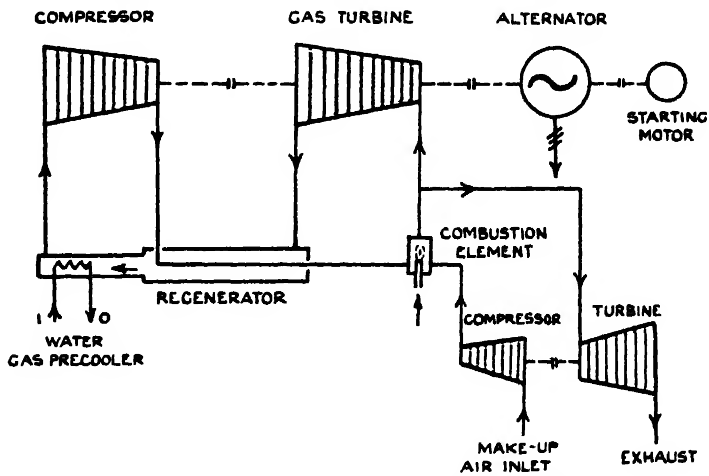

FIG. 642. Internally Fired Closed-cycle Plant.

Heat insulation is placed between the inner and outer casings, and the inner shell is vented into the insulation space. Only the special thin wall steel liners have to withstand high temperatures while the relatively cool outer casing takes the pressure strain.

The hot-air turbine only requires 10 to 13 per cent. of the quantity of cooling water required by an equivalent steam plant.

The time taken to run up from cold is usually one to two hours, depending upon the ambient temperature, but once warm the turbine is able to carry full load within a few minutes of starting.

The use of gases other than air as the working medium is a future possibility, and the closed-cycle system should be adaptable to operation by heat generated in an atomic pile. Helium, which

serves as a moderator for the fissionable material would thus offer the prospect of direct instead of indirect heating.

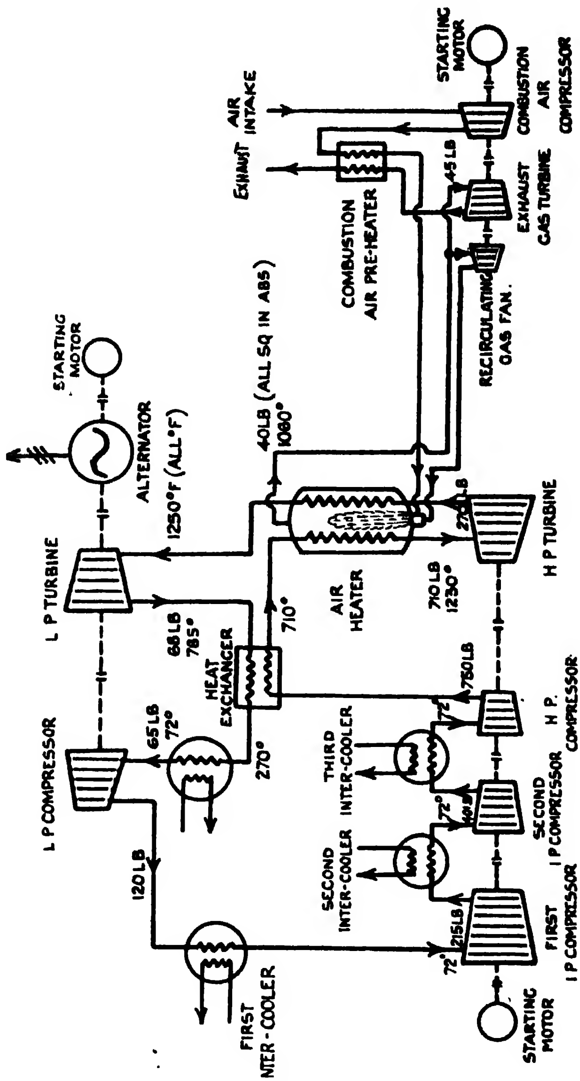

FIG. 643. Circuit Diagram of Hot air Turbine (Closed-cycle).

The closed-cycle system also lends itself to construction in single shaft sets of greater output, in which case the amount of space taken by its larger air heater would not be so predominant.

It is contended that large gas-turbines to be more than the

equivalent steam power should be of the closed-cycle type in which the working medium is indirectly heated, provision being made by various auxiliary components to abstract as much heat as possible from the products of combustion.

A recent 12·5 MW set (Dundee, N.S.H.E.B.) of the closed-cycle type is arranged so that it can be adapted to pulverised-coal and peat combustion. The set will be mainly used for peaks, and also be available to cover any seasonal water deficiencies at the hydro-electric stations.

Special Closed-cycle Plant. The double-isothermal cycle or Ackeret & Keller (A.K.) system (see later diagrams) which, while having the same theoretical efficiency as the Carnot cycle, employs only a small pressure ratio. In the practical application of this cycle, isothermal compression and expansion are only approximately realised. With outer-stage cooling in the compression stage and inter-stage re-heating during expansion, maximum and minimum temperatures are not actually constant, and to that extent the theoretical efficiency is lower than that of the ideal Carnot cycle.

The efficiency being independent of pressure offers the following advantages :—

(1) Any appropriate relationships of maximum and minimum pressures to be adopted and chosen with regard only to constructional considerations of machines and physical properties of materials.

(2) As the power output varies with the pressure level in the circuit, by virtue of the smaller specific volume of the working medium and also the considerably increased heat transmission co-efficients at high pressure, by supercharging the closed circuit above atmospheric pressure the dimensions of the machines can be maintained within small limits.

(3) By arranging to introduce additional medium into the closed circuit the output is increased, and conversely by extraction is reduced. This affords a simple means of load regulation, *i.e.*, by raising or lowering the pressure level in the circuit.

The working medium is clean, therefore blading troubles are reduced ; also heat-exchange surfaces remain clean thus permitting small cross-sections for the heat exchanger elements as the heat transfer coefficients will not deteriorate with service. The combustion circuit is separate from that of the working medium so that almost any kind of solid, liquid or gaseous fuel can be used. Temperatures remain almost unchanged at all loads.

The possibilities of alternatives to air as the working medium are under review, and hydrogen and helium may be utilised. This would enable the output to be increased from any given plant or higher efficiencies might be attained. Combinations of hydrogen or helium with carbon dioxide are also possible.

Sub-atmospheric Cycle. Although, at first sight, this cycle does not appear to be attractive, it may have certain advantages when adequate cooling water is at hand.

Fig. 644, 1—2—3—4—5 relates to a simple form of open-cycle sub-atmospheric gas turbine. The point 1 refers to air in the

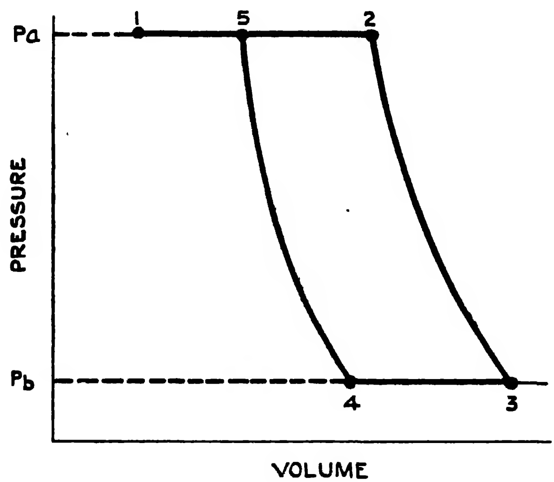

FIG. 644.

combustion chamber, at atmospheric temperature and pressure. Constant-pressure combustion at atmospheric pressure, takes place along the line 1—2; expansion in the turbine to a pressure below atmospheric along 2—3; constant-pressure cooling along 3—4; and re-compression to atmosphere along 4—5; after which exhaust pressure takes place to atmosphere.

The lower pressure P_b is produced by an exhauster; the cooling 3—4 by a water cooler, or, possibly, by direct water injection. The work area 5—2—3—4 is of the same form as that applying to an ideal constant-pressure turbine working with the same overall pressure ratio and compressing air above atmospheric pressure, but the efficiency will be somewhat less since the points 5 and 1 do not coincide (the exhauster will discharge at a temperature greater

than atmospheric) and the result of this is to increase the ratio of heat received to work done.

However, windage losses for the exhauster may be less than for the compressor of the super-atmospheric cycle, since the exhauster blades are moving in a more rarified atmosphere, and if both cycles were equally developed, the difference in efficiency might not be too great. There would seem to be possibilities in a compound cycle utilising exhaust heat from a piston engine either in a sub-atmospheric turbine, or in a turbine working partly above and partly below atmospheric pressure.

If sub-atmospheric working were applied to a closed-cycle machine with external heating, the working cycle would be 5—2—3—4, simply a heat interchanger could be applied to transfer heat to the gas entering the main heating chamber at 5, from the low-pressure gas at 3, before the low-pressure gas passed through the water cooler. This cycle should be as efficient as any other constant pressure cycle, but the maximum temperature might be rather high.

In any sub-atmospheric cycle, the greatest difference between the highest and lowest pressures cannot exceed 15 p.s.i., whatever the pressure ratio, and for this reason the cycle may, perhaps, find an application when it becomes possible, through the development of new heat-resisting materials, to employ greater expansion ratios and so obtain high efficiencies.

COMPARISON WITH OTHER PLANTS

Steam Plant. The theoretical efficiency (Fig. 645) of the gas turbine, referred to the Carnot cycle, is potentially much greater than that obtaining with steam. The full exploitation of this advantage, however, necessitates durable steels, capable of withstanding higher temperatures than those in commercial use.

It is not high thermal efficiency that counts at this stage, since any advance over steam would be much more than offset by the high cost and the growing scarcity of fuel oil.

Since it requires no condenser cooling water, the simple open-cycle can be employed where supplies of water are not available.

To compete with steam, a combustion gas-turbine power unit requires to be operated at above 1,000° F., and to achieve very high efficiencies in its turbine and compressor components. At 1,200° F. for each kW. at the alternator terminals some 4 kW. must be produced by the turbine, the balance being used to compress the gas.

Whereas with steam the Carnot cycle efficiency is obtainable only up to critical pressure (3,206 p.s.i. (abs.) at 705·4° F.) the gas cycle could theoretically attain it, subject to losses in turbine and compressor, and the provision of an infinite number of stages of intercooling and re-heating and a regenerator of infinite size.

Above 705·4° F. the gap between the steam cycle and the ideal cycle widens. Above 1,000° F. the gas cycle efficiency increases approximately three times as fast as the steam cycle efficiency for a given top temperature increase. In view of the low working pressure of the gas turbine, the energy per lb. of gas is small com-

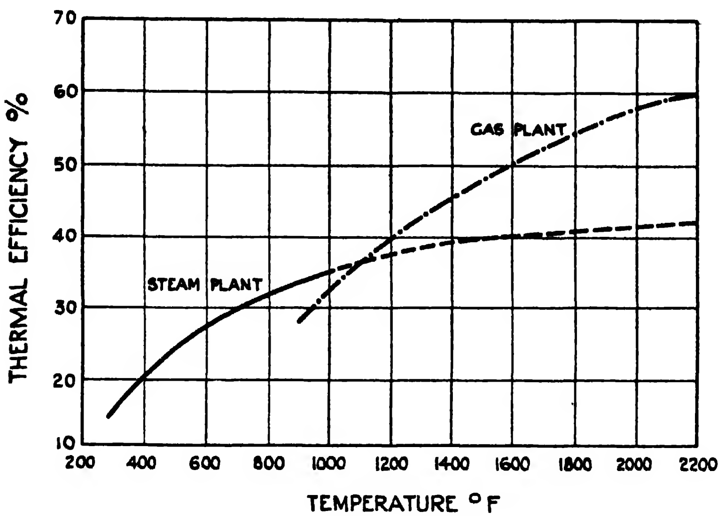

Fig. 645. Comparison between Steam and Closed-cycle Turbines.

pared with that of steam. For example, in a 5 MW, 3,600 r.p.m. simple cycle unit, the gas flow, with inlet pressure and temperature of 88 p.s.i. and 1,200° F., would be about 510,000 lb. per hour compared with 52,500 lb. of steam at 465 p.s.i., 825° F. In this example the ratio of exhaust to inlet volume for the same conditions would be only 3·95 with the gas turbine as against 250 with steam.

If steam cycles could utilise the temperatures of the gas turbine, then steam would show a better efficiency, but comparison in terms of efficiency only is not always desirable.

In this country, coal with a calorific value of 11,000 B.Th.U. per lb., costs up to £2 10s. 0d. per ton, whereas the cheapest oil costs £8 15s. 0d. per ton, with a calorific value approaching 18,500.

This price ratio—almost twice—makes the 17 per cent. efficiency of steam plant about equivalent to a gas turbine operating at 34 per cent. This being the case, the gas turbine as a base load generating unit has little future in this country until coal firing has been attained.

The cubic capacity of the buildings required is about one-half of that for comparable steam plant, which effects considerable saving in capital cost together with the fact that the smaller space necessitated enables gas turbine plant to be installed at selected load centres where steam plant could not be accommodated.

The total weight of material required is considerably less than in an equivalent steam plant, and may amount to a reduction of 50 per cent. or more.

Cooling water is not required for the turbine but circuit air cooling is generally necessary in many cycles. The heat to be removed is greater in the closed-cycle, and is about the same as that rejected to the cooling water from a steam condenser.

The chimney discharge is similar to that of oil-fired boilers, but the temperature is rather higher. The volume discharged to the atmosphere is some six times that of an equivalent boiler plant. Solid grit is absent but sulphur compounds are present so that flue gas washing may in some cases still be necessary. The higher temperature of the exhaust gases improves the chimney effect, and the usual draught plant and grit arresters are unnecessary.

Fewer and smaller auxiliaries are necessary with consequent reduction in auxiliary switchgear and works units. The starting motor is the largest auxiliary unit. The difference in works units varies from 4 to 5 per cent.

Fuel storage is also much less.

Diesel Engine. The most effective, simplest and reliable way of improving the cycle of the internal combustion turbine is to increase the maximum temperature of the working medium or "gas."

Fuel consumption may range from 0·42 to 0·56 lb. per H.P. hour, which is high compared with Diesel engine practice, but on the whole the economic aspects do not differ widely, and any balance in this direction may be outweighed by reduced maintenance and attendance charges on the gas turbine plant or by the lower capital cost of the smaller buildings required.

The advantages of this plant over the Diesel engine are: easier maintenance, improved reliability, lower initial cost, smaller plant

dimensions for equivalent output, less vibration, absence of cyclic variation, and greater starting torque.

Combined Steam and Gas Turbine. From time to time attention has been focussed on the possibility of combining steam turbine and gas turbine power with pressure combustion on the steam side. It is estimated that about three-quarters of the net output of the plant is obtained from a normal steam turbine supplied with steam from a boiler of the Velox type, in which combustion takes place under pressure. Use is made of a supercharged reciprocating internal combustion engine developing only sufficient power to drive its own supercharger and exhausting at a pressure of about 5 p.s.i. gauge.

The exhaust from this unit, being used in the steam generating plant, is expanded in the gas turbine, thereby providing the remaining 25 per cent. of the net output. The efficiency of the steam side is further increased by circulating the feed water through the supercharger coolers, the internal combustion engine jackets, and the usual heater in the gas turbine exhaust.

COAL-FIRED TURBINE

The use of coal instead of oil is considered to be a possibility and is now the subject of research. The main avenue of investigation is that of burning the coal as pulverised fuel in a furnace under pressure and passing the resulting gases to the turbine. An alternative but more expensive method of using coal as the fuel would be to gasify it in a producer gas plant and burn the resulting gas in the combustion chamber.

Means of using coal in the closed-cycle turbine do not appear to have been fully investigated, but the open-cycle turbine may be adapted to pulverised coal operation in the very near future.

Such a development would have a marked effect on national fuel policy, in spite of the additional cost of the plant and the lower efficiency to be expected as compared with oil-firing.

It may be possible to burn coal internally in the cycle, either pulverised or in some special type of furnace ; or to gasify the coal and burn the gas internally ; or to use external combustion, either with open-cycle or with closed-cycle plant. The gasification process may yield by-products of value.

The most likely cycles for coal-fired operation are the simple open-cycle ; the regenerative open-cycle and the regenerative open-

cycle with intercooling. Probably the principal difficulties to be met with coal-firing are coal handling and ash disposal.

The power cost of introducing the fuel into the compression system and of removing the ash was estimated at 10 kWh. per ton, while prior pulverisation may necessitate a further 15 to 30 kWh. per ton.

When using a distillate oil, efficiencies of 98 per cent. could be achieved, but the longer ducts required for coal-firing and increased capital costs would in all probability make it inevitable to use combustion efficiencies not exceeding 88 per cent. Radiation from burning solid-coal particles is more intense than oil and likely to lead to difficulty in cooling the combustion chamber. The radiation comes from a fuel bed or from solid particles suspended in a gas, and the emissivity of the burning fuel is somewhat greater than with oil flame. Further, to promote combustion efficiency the temperature requires to be maintained above 2,052° F., and the presence of ash also brings in constructional problems.

Turbine and blade design require care to minimise the effect of erosion by solids, and the temperature limit would depend on the characteristics of the ash, especially stickiness. The turbine would in all probability require cleaning by washing, and the design should be arranged to facilitate this.

If high-pressure steam is produced and used efficiently it results in a higher thermodynamic efficiency than is likely to be obtained by using a coal-fired gas turbine cycle.

In very large gas-turbine plants, it may prove an economic proposition to generate high-pressure steam in the combustion chamber, and there would be an inducement to put as much heat as possible into producing steam and as little as possible into heating air for the gas-turbine cycle.

The coal-fired gas-turbine would cost more and be less efficient than one using a distillate oil in the same cycle, and with a free choice of cycle, the maximum thermal efficiency would be much less. Coal-fired units could be used economically where the exhaust gases are utilised, either directly or for generating steam, or those in which the gas-turbines became very largely an auxiliary to steam plant.

It has been suggested that factories needing power and heat might be a useful field of application as compared with steam turbines supplied with low-pressure steam éxhausting at 40 to 50 p.s.i. The gas-turbine should enable at least twice as much

power to be generated per unit of heat in the fuel, although with a lower steam heat output.

A new cycle has been suggested in which the turbine utilises clean compressed air of appropriate temperature thus avoiding the flyash difficulties experienced with the open cycles using combustion gases. Combustion of the fuel is effected in a furnace (Fig. 646), which is at atmospheric pressure. The air-heater surfaces and furnace volume are larger, but neither are exposed to high pressure, and mechanical grates and pulverised fuel firing can be used. Only

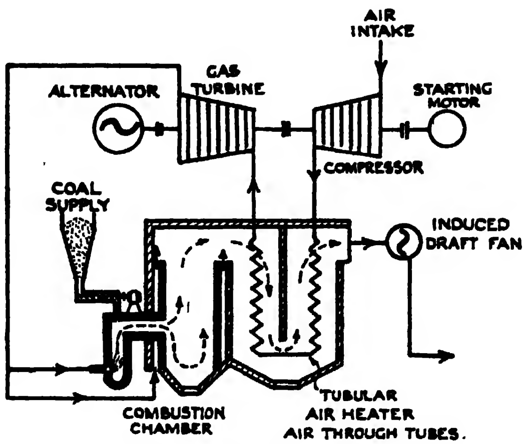

FIG. 646. Coal-fired Gas Turbine.

part of the exhaust air is admitted to the furnace space and the balance is passed through the furnace jacket before mixing with the gases at a point between the furnace outlet and the air-heater inlet. The required draft can be provided by an induced draft fan unless natural draft is adequate.

TECHNICAL PROBLEMS

Turbine Design. Much of the necessary data for the turbine design already existed in steam practice. The chief differences were due to the narrow expansion range of the gas turbine as compared with the steam turbine, and the fact that the gas turbine operated with a medium of almost double the density of steam at comparable conditions. Further, it exhausted at atmospheric pressure, and had a higher exhaust temperature. These factors result in the gas turbine having about the same opening at the low-

pressure end and of similar overall length to an equivalent steam turbine.

The high temperature at which the blading worked fixed the allowable stress if a given life was specified. It has been suggested that for a life of 100,000 hours it is inadvisable to operate with a temperature exceeding 1,200° F.

It may be economically justifiable to run at 1,350° F., and to reblade every 10,000 hours, but future operating experience will be the only way of reaching satisfactory conclusions. The materials used were subjected to a combination of stress, heat and corrosion not found in any other application. Air-cooled hollow blades, apart from difficulties of manufacture, have certain disadvantages, such as their inherent bad shape and the cooling of the gases by the incoming air.

The blade design is more critical aerodynamically than that of the steam turbine, and as the axial velocity at outlet was a greater part of the air energy, this velocity must be reduced as much as possible and an attempt made to diffuse after the blading. To meet such conditions the blade and rotor lengths must be fairly long but the centrifugal force limited the blade length and critical speeds restricted the shaft length. The moving blades are not shrouded or laced. Blading subjected to exceptionally high temperatures is made of material which is resistant to creep and corrosion—either a special austenitic steel or a nickel-chromium base alloy (usually Nimonic 80). Turbine rotors may be machined from solid forgings, alternatives are drum and welded construction.

The speed of output shaft affects the general design, and a 50 cycle alternator must of course run at 3,000 r.p.m., or a sub-multiple of this speed. At 3,000 r.p.m. there is a limit to the volume flow through a single exhaust for given blade and rotor stressing and exit velocity. In the open-cycle compound plant with low-pressure turbine running at 3,000 r.p.m., this limits the rating to about 15 MW for single exhaust and to 30 MW for double exhaust arrangements. The drive may be geared down to the alternator, and in some cases from the high-pressure shafts.

Turbine and Cycle Efficiencies. The effect of turbine efficiency on the overall performance of the plant is somewhat greater than that of the compressor efficiency. This is due to the heat drop across the turbine blading being greater than the heat rise in the compressor. It is essential to attain as high a temperature as possible for the turbine inlet gases.

For optimum efficiency, however, the compressor ratio needed to increase with temperature increases even with the provision of a heat exchanger. Just as intercooling could be used to improve compressor performance, reheating can be used to improve the turbine efficiency. Reheating also improves the output, increases the pressure ratio for optimum conditions and enables the control of the plant for part load conditions to be made more flexible.

Increasing the turbine efficiency by some 6 per cent. will increase the overall thermal efficiency of the plant by about 30 per cent. Very high efficiency makes the plant extremely sensitive to slight variations in blade form, angle and clearance, thus necessitating greater accuracy of workmanship, and generally more maintenance with consequent increase in cost. A reduction of 1 per cent. in the efficiencies of the turbine and compressor (taken as 85 and 84 per cent. respectively) decreases the useful output by some 7 per cent. in a simple open-cycle plant.

There are three ways of improving the gas-cycle efficiency, namely :—intercooling, regeneration and reheating.

Intercooling during compression reduces the work of the compressor (due to the smaller volume of the colder air) by some 15 per cent. for each stage, thereby increasing the useful proportion of the turbine capacity as well as improving the cycle efficiency.

A heat exchanger transfers up to approximately 75 per cent. of the heat of the turbine-exhaust gases to the air entering the combustion element.

Reheating enables heat to be given to the gas (which is about 85 per cent. air) between the turbine stages, and the colder the inlet air to the compressor, the higher will be the cycle efficiency and the output. A 10° change in inlet air temperature will vary the efficiency by some 3 per cent. and the output by 4 per cent. in a simple open-cycle plant.

Probable thermal efficiencies, based on atmospheric temperature of 59° F., are :—

(4–7·5 MW)	14–18 per cent. for uncompounded plant without regenerator.
	20–25 per cent. for uncompounded plant with regenerator.
(10–30 MW)	27–32 per cent. for compound plant with regenerator.

Higher thermal efficiencies can be obtained for plant of expensive

construction, for plant of limited life, or for plant operating at lower atmospheric temperatures.

Using a simple formula for the thermodynamic efficiency of a gas turbine, and the usual symbols,

$$\text{Overall efficiency} = \frac{n_t k - \frac{1}{n_c}}{k - 1} \times \text{air standard efficiency.}$$

Where k is the ratio of positive to negative work in the ideal cycle and is therefore equivalent to the ratio of maximum temperature to compression temperature in the ideal cycle; n_t is the turbine efficiency, and n_c the compressor efficiency. This formula is slightly defective because it makes no allowance for the fuel saved due to the heating effect of the losses in the compressor, neither does it allow for (*a*) variable specific heat or (*b*) the fact that the mass flow through the turbine is greater than the mass flow through the compressor by the amount of the liquid fuel injected into the combustion chamber. Apart from this it gives a close approximation to the overall efficiency of the gas turbine. The formula could

$$\text{be written } n_o = \frac{n_t \,.\, n_c \,.\, k - 1}{n_c\,(k - 1)} \times \text{air standard efficiency}$$

on which the relative importance of turbine and compressor efficiencies is more clearly shown, and it can be seen that for a given value of the product $n_t \,.\, n_c$ the overall efficiency is inversely proportional to the compressor efficiency. (Also see contribution to discussion by Squadron-Leader F. Whittle (now Sir Frank), *Journal I.M.E.*, May, 1939.)

Combustion. The quality of combustion is of extreme importance in the satisfactory operation of these plants. It is very necessary to avoid deposits of residues in the air heater (exchanger) tubes, and at the same time to obtain a well-defined distribution of temperatures in the combustion chamber. The efficient and satisfactory combustion of cheap fuel is a very real problem.

The hot gases delivered to the turbine should be sufficiently free from solids to prevent building-up of solid deposits or the erosion of the blades. Another difficulty associated with the combustion of residual oils is that of dealing with the vapours produced by the presence in the oils of the inorganic salts of such metals as vanadium and sodium. Such salts may be vaporised in the combustion chamber, pass through the high-temperature stages of the turbine

and condense and deposit on blades and heat exchanger elements in the cooler low-pressure parts of the system.

Combustion Chambers. For open-cycle plants, the design is to a large extent standard in so far as the principle is concerned. Various forms of construction are in use, some being all metal while others incorporate sections of refractory materials.

In closed-cycle and partly closed-cycle plants, the chambers are essentially similar to oil-fired boilers.

Compressors. The compressor is more responsible than any other component for the use of low-pressure ratios, and is due to the necessity for obtaining the maximum efficiency. Thermodynamically, a large pressure drop across the turbine means extra efficiency from the turbine, but a point is reached where the increase in power required for the compressor offsets this gain.

In present-day plants it would appear that the compression ratio lies between 3 and 10, the latter figure applying to plants which include intercooling, reheat, etc., whilst the former applies more particularly to simple lower efficiency plants with heat exchangers only.

One method of improving compressor efficiency is by the use of several stages with intercoolers. Multi-stage axial flow compressors are used, having fixed and moving blades unshrouded and with moving blades mounted on a drum or solid rotor.

The axial flow compressor has a comparatively high efficiency, which is essential, otherwise too much of the turbine power will be expended in compressing the air for the operating cycle. Since the axial compressor works at approximately constant volume, air delivery rises as the temperature decreases. It has been found that a lowering of the inlet air temperature by 27° to 36° F. gives almost 25 per cent. greater output, with an improvement of 5 per cent. in efficiency.

In an efficient plant, intercooling is essential, and the most common design of compressor then becomes one with a compressor ratio between 2 and 3. A satisfactory filter is required for cleaning the air before it is admitted to the compressor. When aerofoils are used to compress or expand air, it is essential if efficient operation is to be maintained, that the aerofoils retain their designed profiles.

The problem of air filtration is difficult, and the principal cause of atmospheric pollution is smoke. Possible methods of cleaning are filtering, air washing by water spray and electrostatic precipitation.

Heat Exchangers. A heat exchanger is necessary for almost any type of plant if an efficiency of 20 per cent. or more is to be obtained. The extent to which heat recovery should be employed is largely a compromise between thermal efficiency and size and cost of the heat exchanger.

The combustion heat exchanger or air heater is a principal component of the closed-cycle plant, and its function is similar to that of a boiler in steam plant, as it supplies the heat of the fuel through heat-transmission surfaces to the working medium, which has already picked up the waste heat from the turbine exhaust in a heat exchanger. There is no change in state of the medium as occurs with evaporation in a steam boiler, and compensation has to be provided only for the drop in temperature through the turbine. After the air has passed through turbine and heat exchanger, it is cooled to a low temperature, taken through the compressor and then circulated through the system.

High efficiency can only be attained if the proportion of energy passed out in the exhaust as waste heat is kept low. The difficulty is that of designing one which while being compact retains the satisfactory performance of the conventional type. When this is achieved the gas turbine will have made a considerable advance in compactness.

The great bulk and not too good performance of static exchangers or air heaters embodying encased banks of tubes have encouraged the alternative idea of a capacity exchanger in which a matrix of highly conducting wire is rapidly exposed by rotation, first to hot and then colder gas, transferring heat in the process. Designs appear to vary with the nature of the fuel used, oil, gas or coal.

Some combustion heat exchangers or air heaters employ vertical nests of tubes disposed round a cylindrical combustion space, the tubes varying from $\frac{1}{2}$ to $\frac{3}{4}$ in. dia., and wall thickness of 0·10 to 0·15 in. Either air or gas may be arranged to flow through the tubes. High velocity of internal air circulation permits the tubes being exposed to temperatures approaching 1,850° F. and radiant heating without damage.

A 60 MW, 600 p.s.i. double-heating plant may have a combustion air pressure of about 45 to 75 p.s.i. abs., and combustion gas velocities of between 100 to 160 ft./sec. Air velocities inside the tubes may vary from 60 to 130 ft./sec., and the combustion chamber heating surface is about 0·5 sq. ft. per kW. net output of the plant.

With the relatively high internal pressure and with the closed-

cycle, the heat transmission co-efficients on both sides of the heat exchanger are considerably increased and values vary from 30 to 50 B.Th.U. per sq. ft. per hour per °F. Surfaces of 1·5 to 3 sq. ft. per kW. are approximate and depend on the pressures, and for an overall plant efficiency of 33 per cent., recuperation is about 90 per cent. The weight of the heating surface elements appears to vary between 1·5 to 2·5 lb. per kW., and the tubes are only 0·15 to 0·25 dia. A large number of tubes are built up into a nest, terminating at either end in small collector pipes, and as the maximum temperature of the exchanger is about 850° F., special metals are unnecessary.

Employing a heat exchanger to transfer heat from the turbine exhaust to the high pressure air from the compressor does not improve the specfiic output, but assists the designer by reducing the compression ratio for optimum conditions. This is because there is no need for the turbine to have a large expansion ratio to get the maximum heat from the gas, part of which has already been extracted by the heat exchanger.

Utilising Waste Heat. There may be a field for utilising the heat taken from the compressor intercoolers for district heating.

For a 10 MW plant it is possible to raise 25,000 gallons per hour of water from 130° to 200° F. in the intercooler, and another 55,000 gallons per hour over the same temperature rise by using exhaust heat exchangers. The problem with such plants is to match the electrical and heating loads, and such schemes would raise the thermo-dynamic efficiency of the plant to approaching 70 per cent. By using heat accumulators such a system could also solve some of the economic difficulties of partial load running which are characteristic of the gas turbine.

TYPICAL PLANTS

Parsons' Experimental Plant. Fig. 647 shows the diagrammatic arrangement of this plant, which is rated at 500 B.H.P., and operates at a speed of 6,000 r.p.m.

Air is drawn into the system through the filter by means of the axial compressor, which delivers it at about 50 lb. per sq. in. to the regenerator. Here it takes up waste heat from the exhaust gases of the turbine before passing to the combustion chamber.

"Pool" fuel oil is used, being sprayed through an atomising nozzle and burned by part of the incoming air. The remainder of the air is diverted so as to cool the inside of the combustion chamber

walls before mixing with the products of combustion at the outlet of the chamber.

The resulting high temperature gases are taken directly to the turbine, which is direct-coupled to the compressor and the net available power is absorbed by a Froude dynamometer on the same bedplate, enabling useful output to be measured under all operating conditions. The speed is normally controlled by throttling the fuel supply to the combustion chamber. An emergency stop valve mounted on the turbine shuts down the set by by-passing the turbine if tripped by the overspeed governor at the end of the shaft.

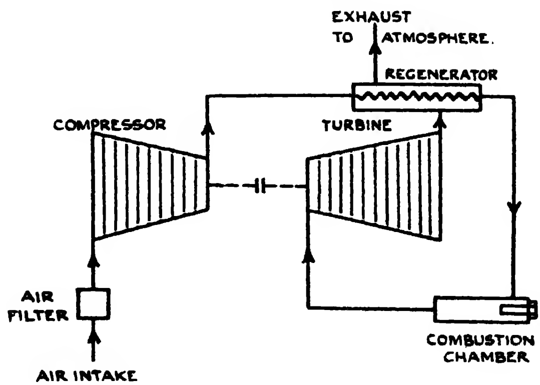

FIG. 647. Experimental Gas Turbine. (C. A. Parsons.)

On starting, the plant is run up to half-speed by an electric motor, after which fuel is turned on and ignited by a low-voltage plug, and on full speed being reached, an automatic clutch disconnects the motor.

The auxiliaries are independently driven lubricating and fuel-oil pumps.

Roumania Natural-Gas Plant. Fig. 648 shows the arrangement of a two-stage plant, each stage comprising a turbine, compressor and starting motor.

The plant is designed for an overall efficiency of 21·6 per cent., using natural gas fuel, with a gas inlet temperature of 1,112° F. Only the low-pressure set, which drives the alternator, delivers surplus power.

On test bed this set was demonstrated under starting and full-load conditions, and with sudden loss of load—

At 0 minutes—supply to ignition rods of the combustion chamber switched on.

1 minute —starting motors switched on by push-button control.

3 minutes—fuel oil ignited.

4 ,, —starting motor cut out at about 1,500 r.p.m. on main turbine, leaving set running under its own power. Speed then increased to 3,000 r.p.m. by operation of the fuel oil valves, when automatic feed regulator took charge (gas inlet temperature to L.P. turbine, 570° F., and of H.P. turbine, 660° F.). The alternator circuit-breaker was then closed and load increased by hand-wheel control as follows :—

6 ,, — 1,000 kW.
7 ,, — 2,000 kW.
8 ,, — 6,000 kW.
9 ,, — 8,000 kW.
10 ,, —10,000 kW. from start.

After a brief run the full load was shed instantaneously by opening the circuit-breaker (air blast). The only noticeable effect

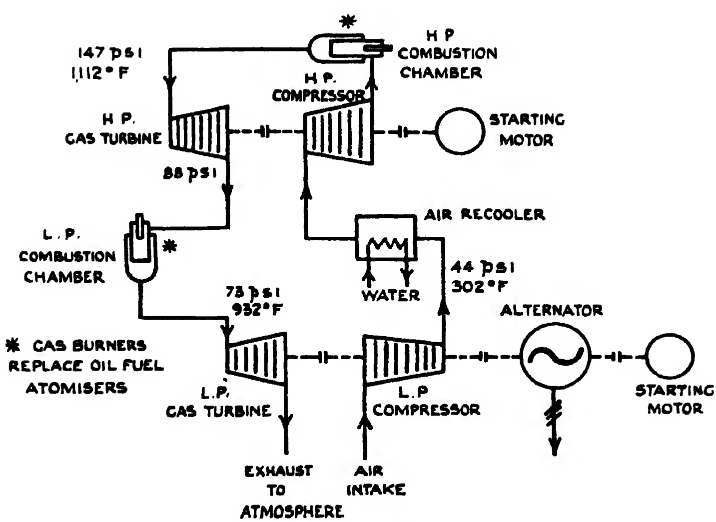

FIG. 648. Circuit Diagram for 10 MW Plant using Natural Gas.

was a rise of speed to 3,300 r.p.m., followed by a quick recovery to 3,000 r.p.m.

Starting and control are very simple and largely automatic.

Load regulation is effected solely by regulation of the fuel inlet valve. The rise in speed from complete loss of load results from the fuel capacity in the combustion circuit, which continues to develop power for a short time after the inlet valve has responded to the new-lost-load conditions.

The largest natural-gas turbine in Roumania is 15,000 H.P.

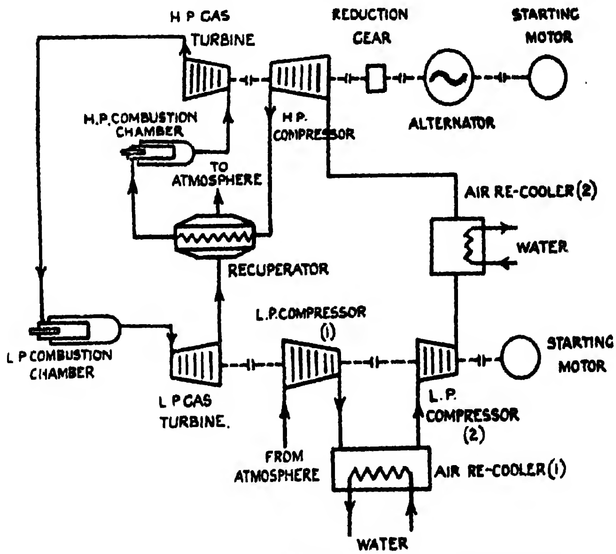

FIG. 649. Circuit Diagram for 10 MW Plant using Boiler Furnace Oil.

and is used for meeting peak loads and serving as a stand-by in a two 9,000 H.P. and one 6,000 H.P. Diesel engine station. The 6,000 H.P. Diesel was converted to run on natural gas.

Peru Oil Plant. From the standpoint of increasing the thermal efficiency, Fig. 649 is of interest. It incorporates both compressor inter-stage cooling and regenerator, which enable a thermal efficiency of 28·3 per cent. to be achieved when burning boiler furnace oil and with a gas inlet temperature of about 1,110° F.

Further possible developments include a combined compressor-recooler, which with a gas inlet temperature of about 1,800° F.

permit considerably higher thermal efficiencies to be realised—30 per cent. and over.

Ackeret and Keller Cycle. Figs. 650 and 651 show one- and two-stage plants, and the data given refer to typical full-load conditions.

For one-stage plants the most favourable pressure ratio from the standpoint of efficiency and constructional requirements is about 3 or 4 to 1, with maximum pressures of 400 to 500 p.s.i., depending on the output. For initial temperatures of from 1,200° to 1,400° F., the temperatures at the turbine exhaust will not exceed 750° to 950° F., and special alloy steels are not necessary for the heat exchangers. The quantity of working air required to be

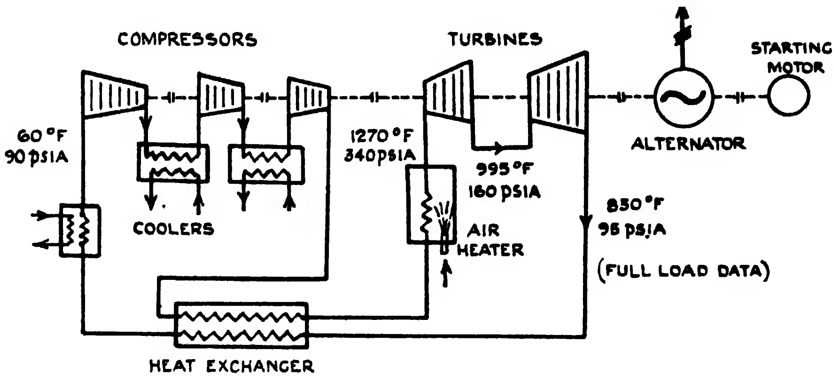

FIG. 650. One-stage Closed-cycle Gas Turbine Plant. (Ackeret & Keller (A.K.) System.)

circulated with the single-stage system is about 20 lb. per sec. for each 1 MW of rating.

With two-stage plants this figure is about 12 lb. per sec. for each 1 MW, and the pressure ratio approximately 10 to 1, while maximum pressures of 400 to 600 p.s.i. a., with back pressures of 40 to 60 p.s.i. a., are anticipated.

For plants of 10 MW and over, pressures of 850 and 85 p.s.i. a. respectively are usual, and even in this case the heat drops are so distributed that the heat exchanger can be constructed without the use of special steels. The theoretical improvement in thermal efficiency attainable by double heating, compared with direct expansion is said to approach 4 per cent., indicative of an overall efficiency of about 35 per cent.

The principle of power regulation with the A.K. cycle is the addition to or reduction of the quantity of working air, thereby

affecting changes in the internal pressure, the operating temperatures remaining substantially constant.

With reduction of load the speed rises and a centrifugal governor causes the discharge side of a combined inlet-outlet valve to open, working air then escaping to a low pressure cylinder. When load reductions are small, a by-pass valve opens and allows air to pass from the high to the low pressure side of the circuit without doing work, but there is no escape of working air. Withdrawal of 20 per

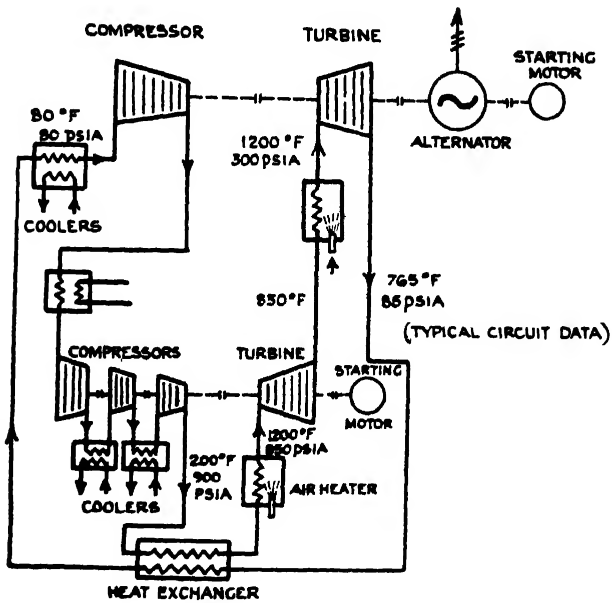

FIG. 651. Two-stage Closed-cycle Gas Turbine Plant. (Ackerot & Keller (A.K.) System.)

cent. of working air from the high pressure side corresponds to complete transition from full to no-load. This method of power control maintains high efficiency at low and intermediate loads.

The difference in auxiliary power when circulating air at high and low pressures is small, and the thermal efficiency, which is dependent only on the maximum and minimum temperatures, remains constant so long as the temperature conditions are unchanged.

Escher Wyss Cycle. In the externally fired closed cycle, the products of combustion do not pass through the turbine and com-

pressor, but heat is transferred from them to the recirculated working gas which is expanded in the turbine.

The gas heater is larger than a steam boiler, because gases are on both sides of the heater. The cycle is thus similar to the steam cycle, except that the working fluid does not undergo a change of state. The problem of using coal should be simpler.

One internally fired closed-cycle system employs an auxiliary gas turbine and compressor to supply make-up air to maintain pressure. It avoids the large gas heater but necessitates the removal of solid matter from the circulated products of combustion.

In both cases turbine control is effected by regulating the gas temperature by varying the rate of fuel supply.

Efficient performance at less than full-load can be obtained by using two turbines, one for variable speed driving a compressor, and the other for constant speed driving the alternator.

Reheating and intercooling improve the efficiency, as they do in the open-cycle, but in the closed-cycle almost full-load efficiency can be achieved by reducing the gas pressure as the load is reduced.

America—Natural Gas Plant. A 3.5 MW plant operates on natural gas which is available. The waste heat from the exhaust is used with a separate heat exchanger to supplement the boiler feed water heating system. This results in additional output from the power station by releasing part of the heating load from the steam plant.

The set is of the in-line arrangement of compressor, combustion chamber and turbine, which is geared to a standard 3,600 r.p.m. alternator and exciter.

Swiss Plant. Fig. 652 shows the diagrammatic arrangement of a 13 MW set, which is also applicable to a 27 MW set built by Brown-Boveri and installed at Beznau. Both sets run from Monday morning until Saturday noon.

Each turbine consists of a high pressure unit and a low pressure unit. The high pressure shaft of the turbine and the compressor of the 13 MW set revolve at 4,750 r.p.m., reduced by gearing to 3,000 r.p.m. for the alternator. The latter speed is adopted for the low pressure shaft as the maximum for its variable speed, and for both shafts of the 27 MW set.

For starting the turbines 280 kW. (high pressure) and 46 kW. (low pressure) motors are required for the 13 MW set, and 630 kW. and 900 kW. for the 27 MW set.

River water for the air coolers amounts to 475,000 gallons per

hour, and the pumps are driven by 280 H.P. motors. The plant outputs are based on air-intake and cooling water temperatures of 41° F.

With crude oil having a lower calorific value of 17,000 B.Th.U. per lb., the thermal efficiency of the 13 MW set is expected to be about 30·6 per cent., and that of the 27 MW turbine, 34 per cent. Including energy consumption of the auxiliaries and losses in transformers, the average efficiency would approach 32·4 per cent.

The recuperator transfers up to 90 per cent. of the heat in the exhaust gases to the air entering the combustion chamber, and is a

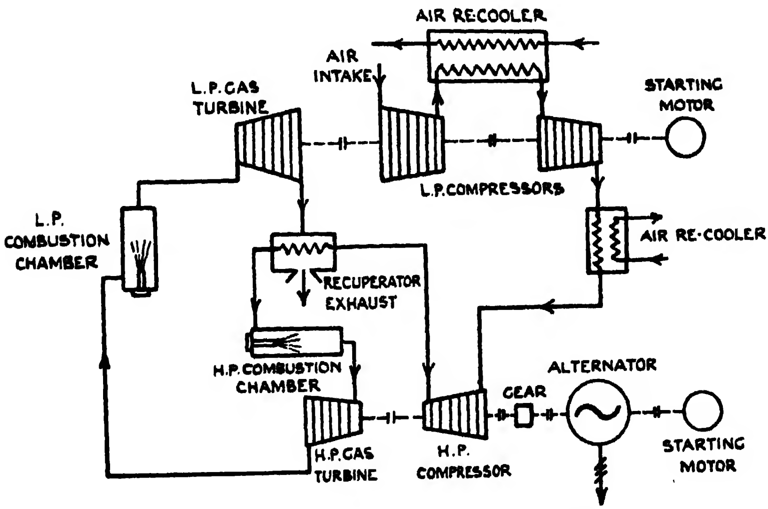

FIG. 652. Two-stage Combustion Turbine with Heat Exchanger (Open-cycle.)

primary factor in raising the thermal efficiency. It adds to the capital cost, but need only be included if an efficiency exceeding 21 per cent. is desired. Its rating can be adjusted to give the lowest overall cost for the running conditions envisaged. Interstage cooling and reheating both improve the efficiency, and further, increase the power for the same volume of air, thereby reducing the price per kW. installed. The water required for the coolers is only about 12 per cent. of that for a steam turbine of equivalent electrical rating. The set can be run from cold and synchronised within ten minutes.

Another Swiss station at Weinfelden has a 20 MW set operating

on the Sulzer high pressure cycle. This consists of three sets of gas turbines, namely, the feed set, with the gas turbine-driven compressor taking air from the atmosphere ; the circuit set, comprising the air turbine with medium and high pressure compressors, and the output set, consisting of the gas turbine-driven alternator.

The principal stationary plant is the combustion chamber with its air heater and the secondary combustion chamber, along with the intermediate recuperators and coolers. The main recuperators and all the coolers are grouped in the basement below the turbine house. The auxiliary recuperators are fitted into the exhaust gas ducts.

The plant is designed for a maximum gas temperature of 650° C. at the turbine inlet and the full load efficiency is expected to be about 35 per cent.

The system of regulation for the turbines is designed to maintain a high efficiency over a wide range of load variation. To achieve this the temperatures of the combustion chambers are kept approximately constant and the variations in output are effected by changing the level of pressure in the turbine circuit.

Three fuel oil tanks are provided near the station, each containing about 500 cub. metres, sufficient to run the plant for 3,000 hours. The fuel oil is too viscous to be used and ignited at normal temperatures without difficulty and it is heated to 100° C. before being passed to the injection system. The heating is done in two intermediate tanks, each having a capacity of 10 cub. metres, which are connected to the steam system. There are steam pipes for heating the oil in the main storage tanks, the supply mains and the tanker vehicles which deliver the oil.

The combustion air required by the gas turbine is taken directly from the atmosphere through a concrete chimney, which adjoins the turbine house. By drawing air from a reasonable height above ground level at a low speed the entering dust is reduced to a minimum. The turbine plant requires 45 cub. metres of air per second, which is about one-half of the quantity which would be required with an open-cycle plant of the two-stage type. The gas turbine unit requires about 235 litres of water per second, and this water is drawn from the sub-soil by borehole pumps. After passing through the plant the water is returned to the ground where it finds its way back to the sub-soil water stream.

Venezuela Plant. The Shell Petroleum Co. have on order a 1·75 MW set to be built by the Metropolitan-Vickers Co. which will

be designed to give reliable service over prolonged periods on base load. It will be installed in one of the oil-fields of the Maracaibo area in Venezuela. Natural gas will be used having the following approximate volumetric analysis : methane, 84 per cent ; ethane, 12 per cent ; and propane, 4 per cent. The turbine will be of the simple open-cycle type with oil-heat exchanger, and the compressor will be an axial flow unit with a compression ratio of 5 to 1.

The turbine coupled direct to the compressor will run at 7,000 r.p.m. and drive an alternator through a single reduction gear at 1,200 r.p.m.

The combustion chambers will be of the flame-tube type placed symmetrically between the compressor and the turbine, round the turbo-compressor coupling. Such a layout should give a straight-through flow of gas, with minimum pressure drop and it also affords easy access to the inboard bearings of the rotor.

The performance data based on ambient air conditions of 14·7 lb. p.s.i. and a temperature of 95° F. are as follows :

Maximum continuous rating	1·75 MW.
Turbine inlet temperature	1,185° F.
Thermal efficiency at alternator terminals . .	15 per cent.

The unit will be started by a 60 B.H.P. motor and the estimated time required to bring it up from cold conditions to full load is about 15 minutes. The quantity of cooling water required for the turbo-alternator oil and air coolers is 150 g.p.m.

British Plants. The first large plant to be ordered for power station work was the 12·5 MW unit for the North of Scotland Hydro Electricity Board. It was manufactured by J. Brown & Co. Ltd., of Clydebank, under Escher Wyss licence and designed to burn heavy "pool" oil, but arrangements are made to resort to coal-firing later.

Two 15 MW units have been built for the British Electricity Authority (one by Metropolitan-Vickers Electrical Co. Ltd., and the other by C. A. Parsons & Co. Ltd.) and are installed in the Trafford Park Power Station and the Dunston "A" Power Station.

Special care was taken to deal with air infiltration in the Trafford Park plant, in view of the surrounding dirty industrial atmosphere. It burns a distillate fuel oil to eliminate ash deposit and is of the compound open-cycle type incorporating one stage of intercooling and one stage of reheating. Also a heat regenerator. The

regenerator comprises six vertical tubular heat exchanger units in which heat is transferred from the exhaust gases to the air after compression. The overall efficiency approaches 28 per cent. and the quantity of cooling water required will be less than half that required by a comparable condensing steam turbine plant.

It has been stated that development work is in hand for the manufacture of plants to utilise peat. These plants will have machines which will cut several hundred feet of peat per day in 6 ft. slices. After collection the machines will mangle the peat and burn it, using the heat so generated for the production of electricity. Apparently peat has proved satisfactory as a fuel for gas turbine operation, since the liquid peat creates steam which is usable and is not nearly so severe on the turbine materials.

A 2,000 kW closed-cycle peat-burning set has also been developed to operate on this fuel with a moisture content up to some 50 per cent. Further drying equipment will enable the plant to take peat of a higher moisture content without loss of efficiency. A 750 kW open-cycle plant is also proposed.

It is estimated that there are some 600 million tons of peat solids available for utilisation in Scotland.

PLANT OPERATION

Reference has already been made to some of the special operating characteristics of some of the typical gas turbine plants described. The starting up of these plants is fairly simple and rapid, and the following is the general procedure for the majority of the medium output plants :—

(1) The oil pumps and intercooler water pumps are run up.

(2) The auxiliary starting motor is run up, and the driving of the high pressure shafts aspirates air which rotates the low pressure shafts also.

(3) Fuel line is opened to the combustion chamber and the charge ignited.

(4) Fuel charge to reheat chamber is ignited.

(5) As both shafts rise in speed the starting motor supply is automatically disconnected, and the speed rises until the fuel valve comes under governor control.

(6) Speed and voltage is adjusted and the alternator synchronised.

(7) Load can be built up on alternator by governor gear control.

Control Systems. The system employed depends to a large extent on the plant cycle adopted. With an open-cycle, normal regulation is obtained by control of fuel flow to the combustion chamber, a governor on the output shaft regulating a valve in the fuel supply line. An overspeed governor can be provided on both the high and low pressure shafts, while some form of over-temperature device can be used in association with each combustion chamber. Throttling of the main circulating medium is not used.

In the partly closed-cycle, valves may be included in the main circuit to regulate the proportion of air which is recirculated.

The usual method of obtaining variable load in the closed-cycle is to vary the density of the air in the closed circuit. This necessitates passing air into or out of the circuit from or to one or more reservoirs under pressure, and a charging compressor and control gear are necessary. The fuel flow has to be regulated simultaneously with the air density.

Fuels. The handling of oil fuel is much simpler than that of solid fuel, and the usual plant consists of pumps and piping.

The storage of oil is also much more economical in space than for solid fuel. The amount of storage required depends on the service hours per annum, and varies for different installations. In one winter stand-by plant of 20 MW rating, tanks having a capacity corresponding to a generated output of 60 million kWh. were provided. Another station provided oil storage tanks of sufficient capacity to permit of one year's operation.

The gaseous fuel most favourable for gas turbines is natural gas, but this is seldom obtainable. The liquid fuels which come up for attention for British plants are Pool Gas Oil and Pool Diesel Oil in the distillate class, and Pool Fuel Oil and Pool Heavy Oil in the residual class. Fuels of the residual class are cheaper, and are used in oil-fired steam power plants and appear to be the economic fuels for gas turbines.

Typical properties of the fuels mentioned are given in Table 101 (p. 804).

The price is about 9d. per gallon, the Pool Fuel Oil and Heavy Fuel Oils being a little cheaper.

The minimum temperatures in the storage tanks are about 45° F. for Pool Fuel Oil and 70° F. for Pool Heavy Fuel Oil. Further heating may be necessary before the oil enters the fuel control system and burners. When starting up a light fuel will be desirable if normal operation is on a heavy grade of fuel oil.

TABLE 101 *Fuels*

Class of Fuel.	Pool Gas Oil.	Pool Diesel Oil.	Pool Fuel Oil.	Pool Heavy Fuel Oil.
Specific Gravity, 60° F. . .	0·84	0·865	0·935	0·95
Viscosity Redwood 1 at 100° F. sec.	34	43	220	900
Gross C.V., B.Th.U./lb. . .	19,600	19,400	18,900	18,750
Net C.V., B.Th.U./lb.. . .	18,360	18,200	17,750	17,600
Net C.V., by Volume, Therms/gall.	1·54	1·57	1·66	1·67

The products of combustion will be free from smoke and grit, but will have sulphur and finely divided ash contents corresponding to those in the fuel.

The fuel consumption varies according to the design of plant, and for efficiencies of 34 to 40 per cent., figures of 0·48 to 0·55 lb. per kWh. are usual.

PLANT LAYOUT

The principal building is the turbine house in which the majority of the plant associated with the gas turbines is installed.

It is similar in many respects to the usual steam plant turbine house having an operating floor and basement, the latter accommodating the pipework, cables, coolers, etc.

The fuel oil storage tanks are arranged outside but adjoin the turbine house, and in some installations the heat exchangers can also be placed out-of-doors.

Fig. 653 (A–C) shows a suggested layout for two 15 MW plants, and it is estimated that the building volume per kW. of plant installed will be about 20 cub. ft.

The rotating parts of the plant form a very small part of the total volume of plant, for it is the intercoolers, combustion chambers, heat exchangers, waste heat boilers and interconnecting ductwork which have to be arranged and accommodated and occupy by far the largest space. Wherever possible the majority of these items can be placed out-of-doors, and so minimise the size and cost of buildings. The in-line arrangement appears best from considerations of design, operation and appearance, while the combustion chamber, heat exchanger, air filter unit and intercooler can be disposed on each side of, and parallel to, set.

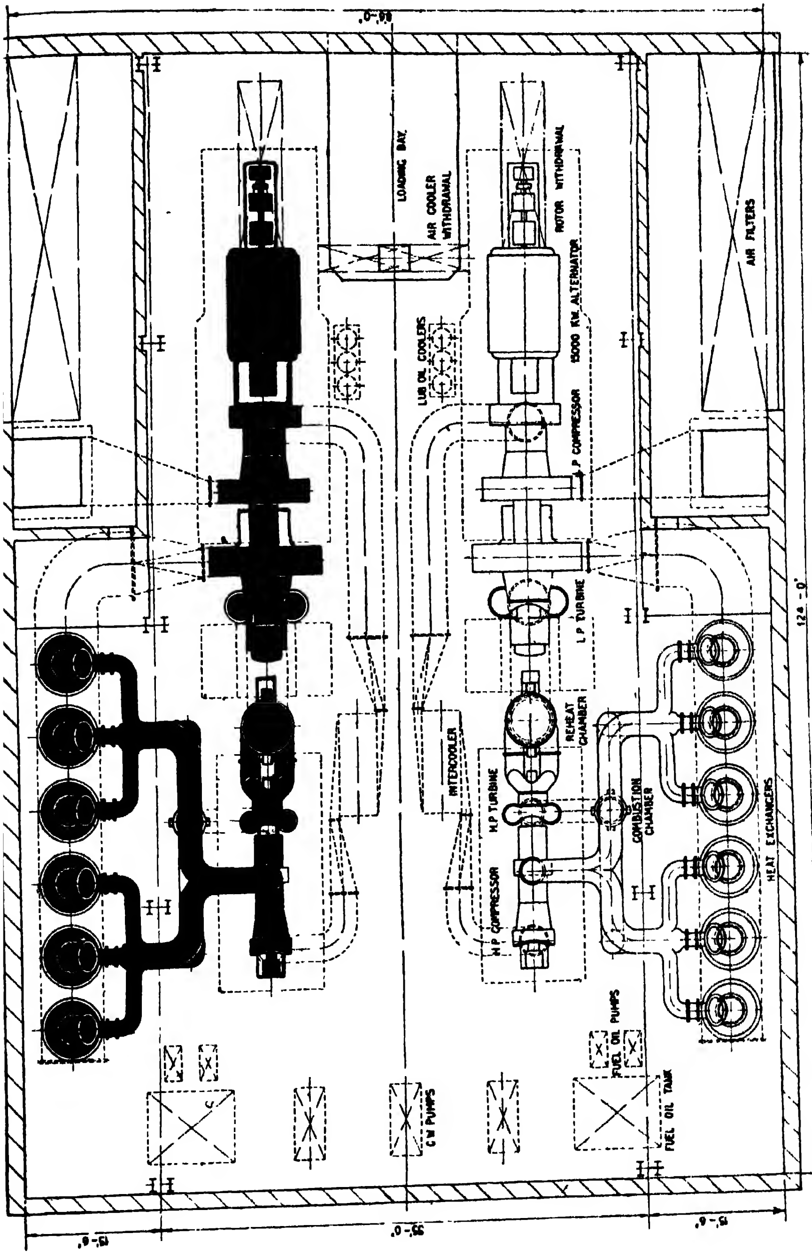

FIG. 653 (A). Layout of Two 15 MW Gas Turbo-alternators (Plan.)

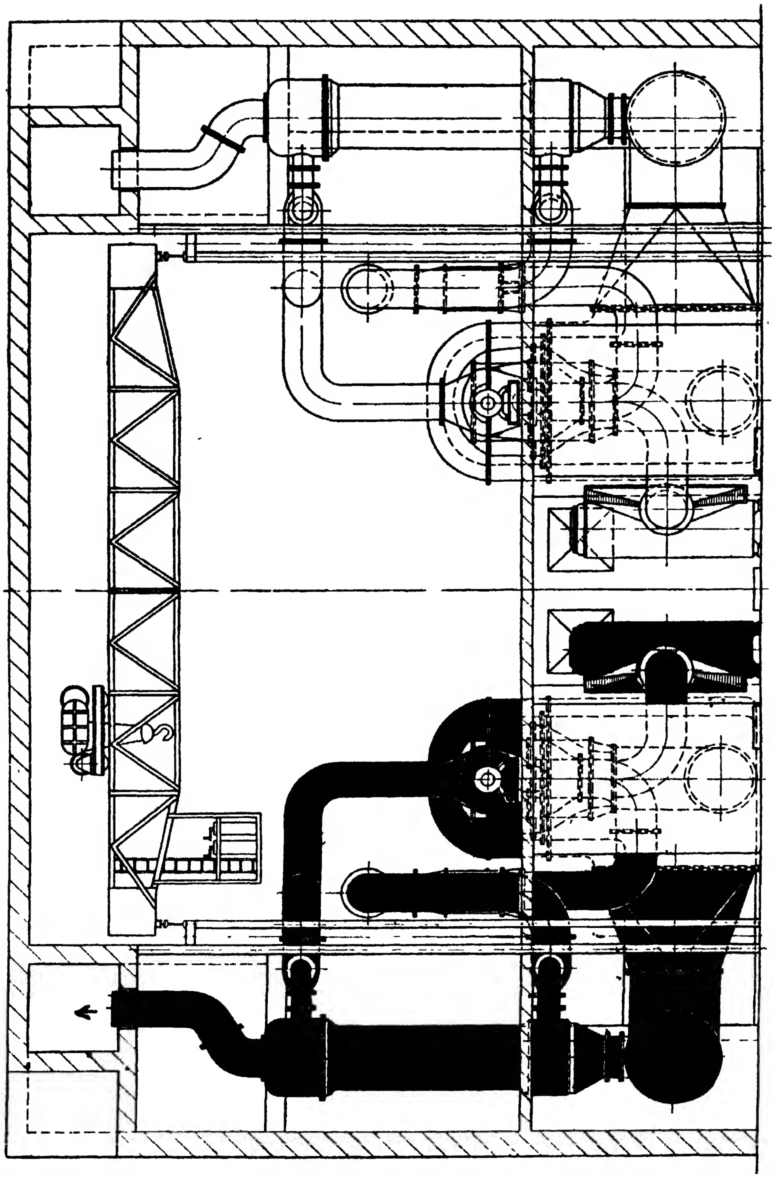

Fig. 653 (b). (End Elevation.)

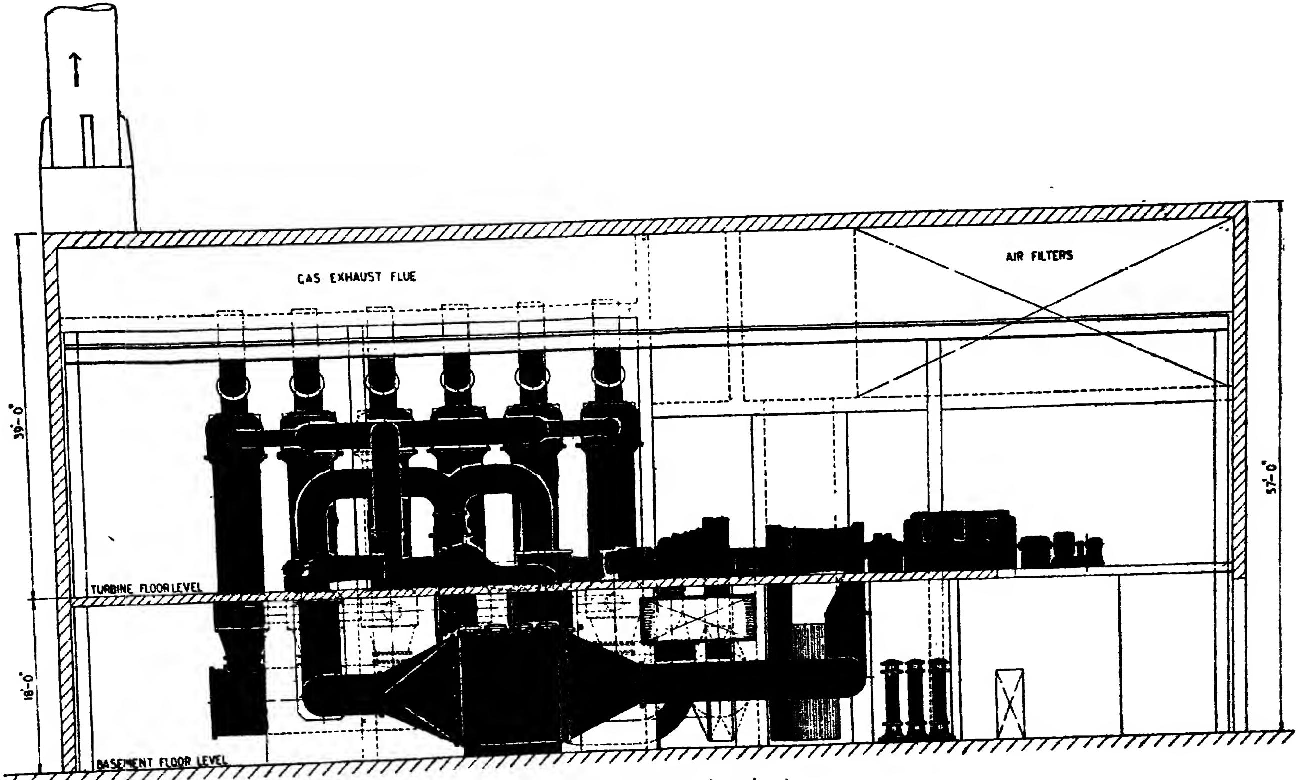

FIG. 653 (c). (Side Elevation.)

The layout of the plant appears to have a very important effect on the overall performance of the plant, as it is possible to incur a loss approaching some 20 per cent. of the power developed in the interconnecting ducts having a considerable number of sharp bends.

Great care is therefore desired in the design and layout of the air/gas circuits. Fig. 654 shows a simplified layout to achieve this

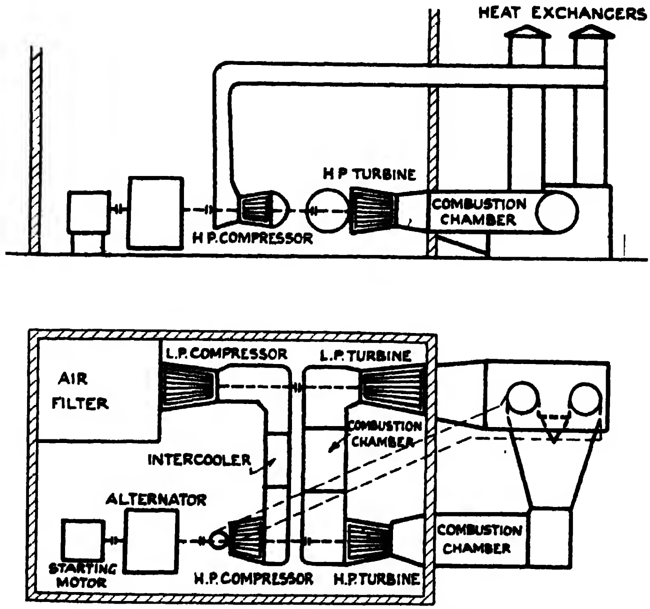

Fig. 654. Gas Turbine Plant Layout.

reduction in losses, but in practice such an arrangement is not always possible.

A bomb-proof 4MW station for stand-by purposes is in operation at Neuchatel, the leading dimensions of which are: 60 ft. long, 17 ft. wide, 26 ft. deep. The space occupied is therefore about $\frac{1}{4}$ sq. ft. per kW. (4 kW./sq. ft.) and 6·6 cub. ft./kW., which includes a small Diesel-driven alternator for affording a supply to the starting motor in the event of complete failure.

COSTS

In a comparison (1948) of various forms of heat engine it is shown that a 25 MW steam turbine with oil-fired boiler and steam conditions of 1,180 per sq. in., 930° F. would cost approximately

£19 per kW. installed and consume about 0·65 lb. of oil per kWh. produced.

For a gas turbine plant of equivalent rating, the corresponding figures were £19·5 and 0·57 lb., and for two 12·5 MW sets the average figures would be about £25 and 0·61 lb.

Two 12·5 MW Diesel engine sets would cost about £32, with a fuel consumption of 0·52 lb. per kWh. Oil storage tanks for 3,000 hours running are included but no transformers or switchgear are provided for.

Typical costs for a 40 MW set are as follows :—

	£
Site	15,000
Buildings, Sidings, Roads	230,000
Gas Turbine Plant, Storage, Lifting Gear	555,000
Switchgear, Transformers and Cables	125,000
Total	£925,000

or £23 per kW. installed.

Allowing 4 per cent. interest, 4·5 per cent. for amortisation (based on seventeen years life at 3 per cent. interest or renewal reserve), and 1 per cent. for maintenance, the annual charges amount to 9·5 per cent. of the capital, *i.e.*, £2·18 per kW.

Average fuel consumption per kWh. would be about 0·65 lb.

The standing charges per kWh. generated would be at the rate of

$$\frac{2{\cdot}18 \times 240}{1{,}000} = 0{\cdot}524\text{d. per } 1{,}000 \text{ hours.}$$

With oil at £8·5 per ton, the fuel costs are :—

$$\frac{0{\cdot}65 \times 8{\cdot}5 \times 240}{2{,}240} = 0{\cdot}58\text{d.}$$

Assuming that the operating staff consists of three men per shift, the operational wages would be about 0·007d.

The overall figures per kWh. generated are thus 1·111d. for 1,000 hours ; 0·849d. for 2,000 hours, and 0·761d. for 3,000 hours operation per annum.

In many installations the total cost per kWh. is expected to be about the same as for a high-head hydro-electric plant, but perhaps from two to three times that for a low-head plant. As about one-half of this cost is divided equally between fuel and capital charges, whereas with a hydro-electric plant capital charges

would account for almost the whole, this gives the gas turbine a decided advantage when used for stand-by and peak load operation.

The overall thermal efficiency will also be higher during the critical winter months than in the summer owing to the greater density of the colder air.

The capital cost of a gas turbine plant having an efficiency of 34 per cent. is said to be lower than that of a Diesel engine, but approximately 33 per cent. more than that of a steam plant of 26 per cent. efficiency. It is difficult to obtain reliable information regarding capital costs, but it has been suggested that gas turbine plants may cost anything from £25 to £35 per kW., as compared with £40 to £50 per kW. for the comparable steam plant.

The gas turbine plant is economic for a wide range of load conditions where liquid or gaseous fuel is very cheap. In this country, with the present prices of coal and oil, this plant is economic only for low load factor conditions.

CHAPTER XXVII

WIND, ATOMIC, AND OTHER POWER PLANTS

Wind Power Plants. The force of the wind has been utilised for the production of mechanical power for generations, but the installations have been only on a small scale. Just as hydro-electric power stations have developed from rather primitive water wheels, it is perhaps reasonable to assume that similar progress may ultimately be made in the field of wind power.

The practical inconvenience attaching to the utilisation of wind power, arising both from the intermittence and unreliability of the source of energy, and from the large size of the plant in terms of output, have almost restricted its use to small sets and to duties for which continuous service is not essential. Both in degree of variation and the length of periods of deficiency, wind power probably has a marked advantage over water power, which may be affected not just by dry seasons, but also dry years. In the development of large sets, the questions of cost—construction and operation—have an important effect. It has been suggested that towers would approach 500 ft. in height, as the difference in energy content of the wind at this height has been found to be as much as three times that at ground level.

The principal claim for wind-power plant is that it may be installed in any locality where the topographical and meteorological conditions are suitable, and requires no outside supplies for its operation, except for a stand-by battery and lubricating oil, etc. This makes it especially suitable for isolated situations in which electric power is not available, and both attendance and the provision of fuel for a thermal plant would be difficult or impracticable.

The choice of site will depend on a number of factors, some of which are : windy area, scattered populations, economic advantage in fuel-saving (oil or coal used), automatic operation. The total energy in the wind cannot be utilised as this would mean stopping the air stream completely in which case the stagnant air would never leave the downstream side of the windwheel.

Taking the density of 1·293 grammes per litre for dry air at 760 mm. and 0° C., the value of the total air stream energy $\frac{MV^3}{2}$

would approximate to $0{\cdot}65V^3$ watts per sq. metre, where V is the velocity in metres per second. Alternatively in British Units this energy is $5{\cdot}38\left(\frac{V}{10}\right)^3$ watts per sq. ft. where V is the speed in m.p.h. For a steady speed of 18 m.p.h. this corresponds to an energy flow of 270 kWh per annum.

The actual energy flow will be less than this as the air will not be dry and the pressure conditions obtaining, especially during periods of strong winds and at the altitude of the windwheel, will be less than 760 mm., and more than 0° C.

Data is at present lacking as to the percentage of the wind energy which can be utilised by a wheel. One authority has suggested 40 per cent. in which case the figure of 270 becomes more nearly 108 kWh per sq. ft. per annum.

The output in kW $= \frac{2{\cdot}14AdV^3}{10^3}$ where A is the area swept by the windmill, d the density of air and V the wind velocity in miles per hour. In practice, the amount of energy which can be brought to generator terminals is probably in the region of 6–10 per cent.

A typical arrangement is shown in Fig. 655. Perfect and continuous balance is not possible, as the blade weight may increase considerably with ice loading. On the output shaft, between the gear casing and the hydraulic coupling, there is a friction clutch connected to a motor-driven turning device, which has a brake. When the plant is shut down, the clutch can be closed and the brake on the turning device applied. The turning device may be used to set the blades in any desired position. The alternator is rated at 1·0 MW at 0·8 power factor, and generates three-phase current at 60 cycles, and 2·3 kV. The cables are connected to slip-rings mounted on a slip-post, and brushes on the rings are connected to cables leading to a 44 kV. step-up transformer which is connected to the main electrical network.

Possibly the most enterprising project was that of Honnef, of Berlin, who contemplated building a 50 MW wind-turbine unit around about 1936. This was to be constructed on a steel tower and to carry five generating sets.

Both technical and economic considerations require that a reasonable approach should be made in embarking on any project of some size.

In 1929 a two-bladed turbine unit, 65 ft. diameter, and carried on a steel tower, was built at Bourget, in France, while in 1931

a 100 kW. unit was constructed near Yalta, in Russia. This latter plant had a two-bladed wind turbine 100 ft. diameter, and ran in connection with a peat burning station some 20 miles away.

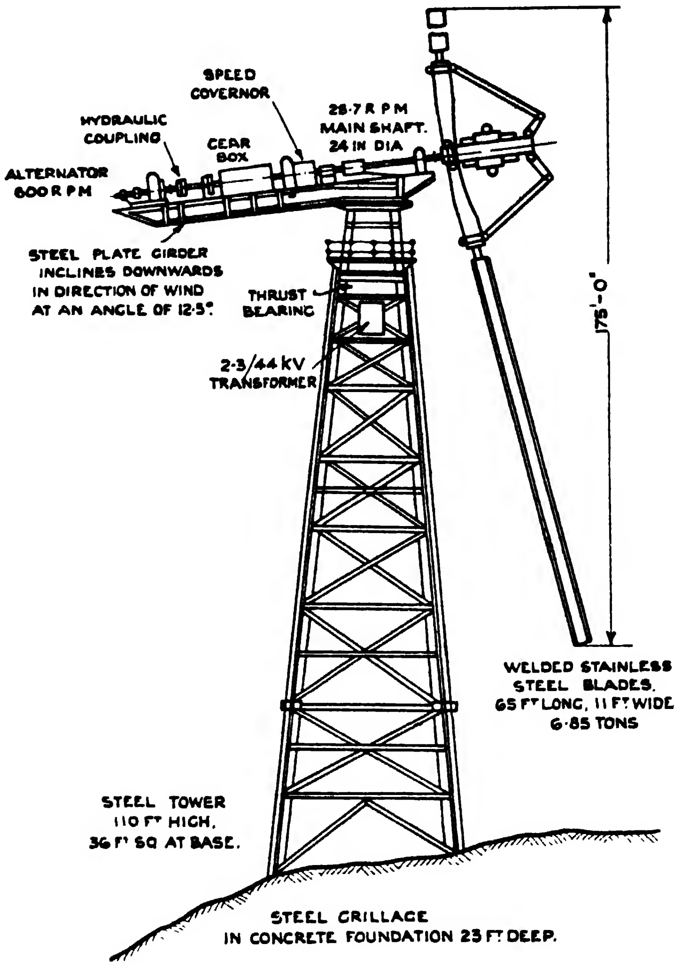

FIG. 655. Wind Power Plant.

If progress is to be made in utilising wind power on a considerable scale, it is necessary that the wind-power units should be connected to a system supplied by steam, Diesel and/or water-power stations. Only in this way can the intermittent service rendered by the wind be utilised and full benefit be derived from periods in which winds are

more than usually constant. A 1·5 MW unit with the alternator running at 600 r.p.m. and driven through gearing by a 200-ft. diameter wind-turbine running at 25 r.p.m., and mounted on top of a 150-ft. tower, had been in operation in America for some years. Ice troubles were encountered. The load could be varied by adjustment of the blade pitch, and outputs of 1·5 MW obtained with winds of 70 miles per hour. Some time later one of the 8-ton blades broke off at the root and was thrown a distance of about 750 ft. The machine was subsequently dismantled.

Another type of wind generator is being developed which is to the designs of M. Andreau. The propeller itself comprises two hollow blades of aluminium alloy, having shaped vents at the end. The coupling between the propeller and the alternator which is situated at the base of the hollow tower is entirely pneumatic. An experimental set of 100 kW is under construction and test.

Wind-power offers some possibilities in this country, though only on a very small scale, for saving coal. Like the Severn Barrage, it has no firm kilowatts. Research is being carried out by the British Electricity Authority, and an expenditure of some £25,000 has been approved for the installation of an experimental wind generator of 100 kW. capacity, and also for a number of smaller units, probably of 10 kW. each. The experiments will be carried out on the high ground of Cornwall and West Wales, and if there appears to be an economic case for developing this method of generation, more plants could be erected elsewhere and connected to the electrical distribution systems.

The North of Scotland Hydro Electricity Board are experimenting with a 100 kW. set (John Brown & Co.) in the Orkney Island. This set will afford a supply point on the 11 kV. system some 20 miles from the Diesel engine station at Kirkwall. Its output will be determined solely by the wind available and since its capacity is small compared with the Diesel plant, its operation will probably be unnoticed at the power station. Its capacity is less than the minimum summer night demand, and it should never require to be shut down for lack of load. The frequency, and therefore the speed of the windwheel will be controlled at the Diesel station.

There were apparently three principal reasons for choosing 100 kW. : (1) It represents a reasonable increase in size compared with existing machines ; (2) limits capital expenditure ; (3) allows the use of several standardised pieces of equipment developed for other purposes.

The data to be obtained are : annual output, degree of reliability and performance of individual parts for future larger designs.

Meters will measure alternator output and consumption of control circuits, number of starts, hours of operation in each year, hours shut down because of very high wind. The tower is to be of steel with its foundations on solid rock ; the blades will be about 30 ft. long and the nacelle about 80 ft. above ground level. The nacelle will contain a gear box and alternator and will rotate to maintain the rounded end facing the wind.

Reliable costs are difficult to obtain, but the following appear to be representative of Dutch and American practice :

25 kW.	£92 per kW.
1,500 ,,	£55 ,, ,,
2,500 ,,	£50 ,, ,,
6,500 ,,	£48 ,, ,,

With an output of 4,000/5,000 kWh. per annum per kW. the costs appear to be :

0·25 pence per kWh. at good sites.
0·40 ,, ,, ,, ,, moderate sites.

Atomic Power Plants. It is anticipated that in the very near future the production of mechanical and electrical power from atom splitting will be progressing beyond the experimental stage, but some doubt exists as to whether electrical energy can be produced more cheaply than by burning coal. An American scientific adviser has suggested that atomic power would be an economical proposition where coal costs exceed 10 dollars per ton (1949).

Atomic-energy release in the crude form of moderate-temperature heat has been going on for some years in some experimental plants.

The true power piles now under consideration will operate at temperatures suitable for modern high-pressure steam power plants. The pile will heat some fluid such as molten bismuth or sodium potassium alloy that can attain high temperatures without creating high vapour pressure. This molten metal will convert feedwater into high-pressure steam in a tubular heat-exchanger, or, alternatively, heat the air supplied to a gas turbine (Fig. 656). Moderators may be of graphite, heavy water and beryllium.

The splitting of 1 lb. of plutonium, or U 235 atoms, yields $11{\cdot}4 \times 10^6$ kWh. in heat form, and conveyed to a gas turbine or steam turbine through molten metal and a heat-exchanger, this

could produce from $2{\cdot}5 \times 10^6$ to $3{\cdot}5 \times 10^6$ kWh. of electrical energy.

Uranium and thorium, the two known atom fuels, are fairly plentiful, but rather expensive. They are the two heaviest metals existing on this earth ; the two heaviest of the chemical elements that are present in the earth's crust. These materials, in certain circumstances, can be made to become unstable and to transform themselves into ordinary chemical elements, iron, nickel, silicon and calcium, and in that process set free a considerable amount of energy ; almost three million times as much energy in weight as the burning of coal. One lb. of these materials burned in this particular way will deliver the energy at present derived from

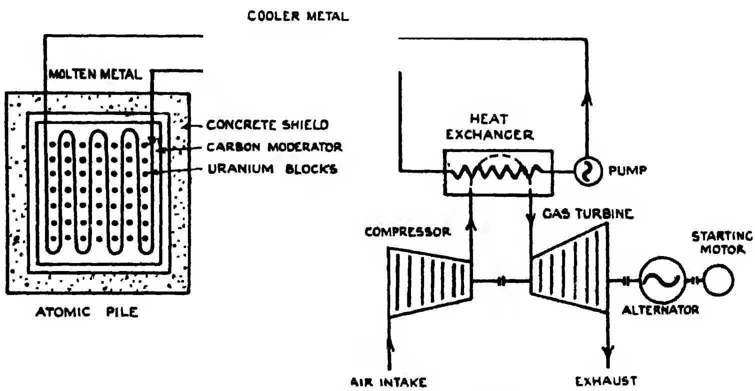

FIG. 656. Uranium Power Pile.

1,500 tons of coal. The biggest job of transmutation is the manufacture of fissionable material, that is, the conversion of U 238 into plutonium in the atomic pile as a by-product of the chain reaction in U 235. Likewise the flying neutrons in the pile can convert relatively cheap thorium into a fissionable form of uranium.

Uranium weighs about 12,000 lb. per cub. ft. and is plastic but so abrasive that special cutting compounds are required to keep it below the ignition point while being machined to shape. It is said that an atomic power reactor of 10 MW at 25 per cent. thermal efficiency would have to develop 40 MW of thermal energy and therefore use $1\frac{1}{2}$ oz. of fuel per day. Operating one year at 100 per cent. load factor would burn up 33 lb.

It is estimated that a 30 MW atomic reactor requires some 300,000 cub. ft. of air per minute at speeds of 40 m.p.h. in the main

duct and hundreds of m.p.h. in the passage ways through the graphite areas. Each of the five blowers requires a 1,500 H.P. motor. The weight of the reactor is some 20,000 tons giving a loading of 3 tons per sq. ft. and the foundation is from 35–40 ft. deep. Steelplate for protective and structural purposes is from 10–20 in. thick. Each plate like the enclosed graphite blocks, is keyed to the adjacent ones to prevent straight-line leakage of radiation.

Atomic-power plants have a number of characteristics which affect them from a commercial point of view.

(1) Atomic-power is produced most economically in large plants of 100 MW and over.

(2) Power output is instantly adjustable from zero to an upper limit, set only by the capacity of the heat-removal system to prevent overheating the pile.

(3) Like a hydro-electric plant, the initial cost is high and the fuel cost very small. Once an installation is completed, the load carried will have but little effect on the operation cost. Base-load operation will be favoured just as in a hydro-electric plant with unlimited water storage.

(4) There are no problems of fuel transportation, as the fuel used is more or less in terms of lbs. rather than tons. The power plant can, therefore, be sited to suit the electrical power desired, irrespective of topography, inaccessibility, etc.

There is at present no means of directly converting to electricity the energy released in an atomic pile, or nuclear reactor, but the accompanying heat could be extracted by pumping liquid, or a gas, through the pile, and then circulating the heated fuel through a form of heat-exchanger which would generate steam for use in turbo-alternators. Thus, an atomic pile, with some auxiliaries, would simply replace a fuel-fired steam generator, and it would appear that the initial cost of an atomic power plant would, at least, be as high as that of the fuel-fired plant under normal conditions. It is possible that the cost of nuclear fuel will be competitive with that of other fuels. There is the possibility that atomic energy, because it is an extremely concentrated source, may offer economical electric power. Atomic power plants, to be efficient and economical, will of necessity be of large capacity, and may require a chemical plant as an adjunct to reclaim partly used fuel.

One of the difficulties with these plants, will be that of disposal of the products, which are highly radio-active materials giving out large quantities of gamma rays—rather like X-rays; and they

are shot out with high energy, destroying living matter through which they pass.

The products of a 400 MW power station would be equivalent to something like 100 tons of radium daily, and if this material were distributed uniformly over Great Britain, then the products from such a station running on nuclear fuel would kill everyone within an area of about 100 square miles. The problem of the disposal of these nuclear ashes still remains unsolved.

Other technical problems still have to be overcome, such as running these plants at a sufficiently high temperature to be able to supply either steam or gas turbines, and operate efficiently. Problems connected with the corrosion of these materials, uranium and thorium, which in the metallic form are somewhat like magnesium. If heated to a high temperature they burst into flame, and if brought into contact with water they rapidly hydrolise, so that some form of protection has to be given to these materials.

There also exists the possibility of using hydrogen, which is a very common substance, for all water consists primarily of hydrogen. It is necessary to treat the hydrogen in the way the sun does, and build up from it heavier chemical elements like oxygen.

It would then be possible to derive from this hydrogen about ten times as much power per lb. as from uranium or thorium—about 100×10^6 units per lb. of hydrogen burned in that way to form heavier materials. It is still required to know how to heat the hydrogen to a sufficient temperature—estimated to be over 1 million degrees. Gases can now be heated to several million degrees by passing electrical charges through them, and by concentrating the magnetic discharge from various electrical fields. The potentials with which the nuclear physicist deals are always reckoned in millions of volts.

It has been stated that so far as potential energy is concerned that one kilogram of pure uranium completely utilised would be equivalent to 2,500 to 3,000 tons of normal quality coal. The cost of uranium (1950), about £15 per kilogram, is equivalent in relation to its return to coal prices at about 1½d. per ton. If hydrogen could be used it would furnish a fuel ten times as efficient on a weight-for-weight basis as uranium.

There appear to be four major problems in the development of atomic power plants, namely :—

(1) To make a casing for the reactor which will withstand high temperatures, corrosion, and intense neutron bombardment.

(2) To devise a fluid to circulate round the reactor and transfer the heat to the heat exchanger.
(3) To seal this circulatory system to prevent loss of efficiency and to protect against radiation.
(4) To shield all plant and to dispose of radio-active waste material.

The atomic power station which is now being erected at Calder Hall, Cumberland, to examine the technical problems and economics of this form of generation and to supply energy to the nation grid system, will consist of two graphite-moderated gas-cooled natural uranium reactors. These reactors will have an active core about 30 ft. in diameter, which will be contained in a pressure vessel of 40 ft. in diameter. They will each be associated with four steam-raising towers about 80 ft. high, a typical sectional elevation of which is shown in Fig. 657. The maximum surface temperature of the fuel in the reactors will be about 400° C. and the heat generated in them will be conveyed to the steam plant by CO_2 at a pressure of some 100 lb. per sq. in. The hot gas will give up its heat to the pre-heating, evaporating and superheating sections of the plant and after passing through the steam-raising towers will be returned to the reactors blowers and the cycle repeated. Use is made of a double-pressure steam cycle in order to obtain the maximum efficiency. The complete towers and the associated feed pumps and other equipment are being constructed by Babcock & Wilcox Ltd. There will be separate sets of steam raising plant, including high pressure and low pressure economisers, evaporators and super-heater sections and feed pumps. To obtain the maximum heat transfer within the towers all the heating surfaces will be of steel-tube construction to give an extended surface. An interesting feature of the station will be that chimneys in the accepted sense will not be necessary as no coal or oil will be burned. Two comparatively small vent pipes will be provided for extracting any heat from the reactors which is not given up to the steam towers.

The turbine plant by C. A. Parsons is designed so that the low pressure section can be supplied both with live steam and with steam that has been expanded in the high pressure blading.

Circulating gas blowers and piping are also being supplied by this firm.

The pressure vessels of the reactors are being supplied by Whessoe Ltd.

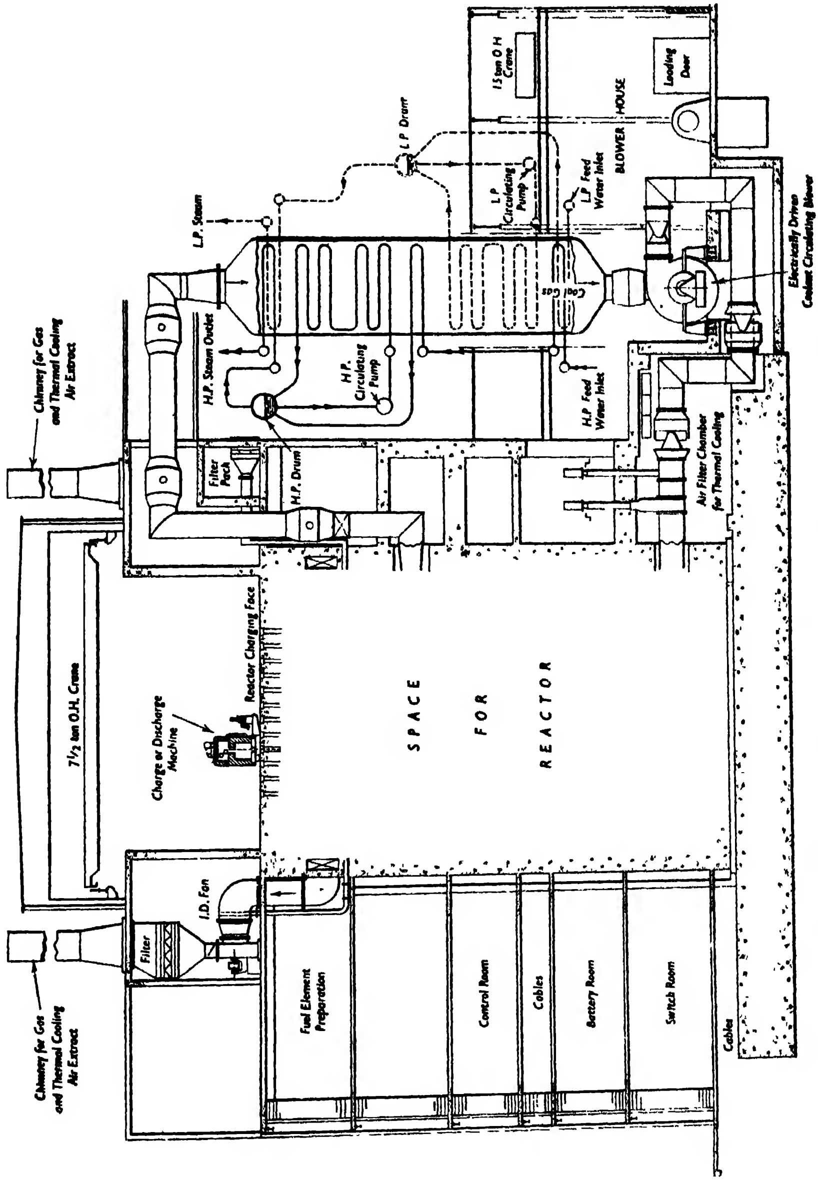

FIG. 657. Sectional Elevation of the Thermal Reactor at Calder Hall Power Station.

Natural Steam Plants. Such plants (Figs. 658 and 659) are in use in Italy and utilise boracic steam jets found at Larderello. The steam is supplied direct to the turbine, with low pressure discharge in a mixing condenser which is fitted with a turbo-vacuum for extracting the gases.

Technical problems had to be overcome before this system could be applied in a practical manner. The turbo-vacuum equipment is

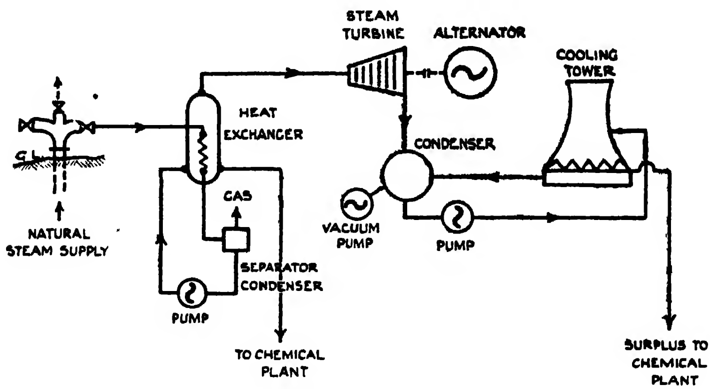

FIG. 658. Natural Steam Jet Plant. (Italy.)

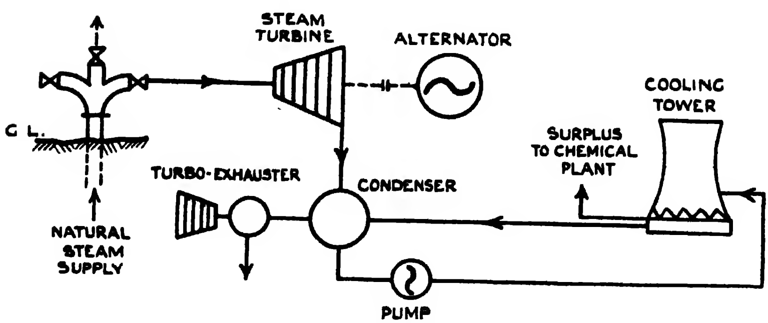

FIG. 659. Natural Steam Jet Plant. (Italy.)

made of special steel to resist corrosion by the gases contained in the steam. It is now possible to limit the steam consumption to 10 kg. per kWh. generated, resulting in some 50 per cent. of fuel saving over the pre-war (1939) plants, and 25 per cent. over the new sets.

Two stations, each having an installed capacity of 250 MW, are understood to be in operation. The wells driven are some 1,000 to 2,000 ft. deep; 140 produce about 4½ million lbs. of steam mixed with non-condensible gases.

The steam conditions of these natural jets appear to vary somewhat and figures of from 5 to 27 atmospheres at temperatures of 140° to 215° C. obtain. Very complete technical data are given in the publication referred to in the bibliography. On one New Zealand plant the geological structure is a hard thick shell of subsurface pumice rock, the lid of an enormous cauldron containing and compressing steam formed by subterranean heating of water. Site tests are carried out to prove that additional tappings does not result in loss of pressure. A 10 MW plant is operated from a 4 in. bore which is estimated to have an output of some 15 MW. Superheated " dry " steam escapes from certain natural vents at a fairly high pressure.

Electrostatic Power Plants. A Frenchman, Felici, has suggested the use of electrostatic generators. He has shown that if such machines are designed correctly and placed in a compressed gas of low viscosity, like hydrogen, with arrangements for the collection of the charges which are induced on the conductors, electric power can be produced rather than high voltages. It can be generated without incurring any iron and copper losses, the only losses being those due to windage of the hydrogen with which the plant is filled.

The power output per cubic yard of machinery is said to be about the same as that obtained by the present-day alternators.

A further advantage is that the power is generated as D.C. power at any desired voltage, and the system is especially economical at voltages of over half-a-million volts.

In a system generating directly at 1 million volts D.C., the machine cannot be damaged by short-circuit, and it is low in capital cost, and cheap to maintain.

Electrochemical Power Plants. This form of generation of electrical power dates from 1800, when Volta showed that a continuous source of electricity could be provided by a simple and inexpensive cell. The chemical energy of the cell put into reactants is turned into electricity when the cell is discharged. In general fuel cells involve reactions between carbon and oxygen, or between other chemical substances. The carbon-oxygen type is known as a direct fuel cell. One type of fuel gas cell used depends on the conversion of highly reactive carbon into a water gas which is subsequently oxidised. This takes place in the presence of electrodes and solid electrolytes to produce electricity. Present indications are that the power generated by this process would be most suitable for high-load factor consumers. Experimental work done indicates that the cost

of electricity so produced may be attractive to industries requiring very large amounts of electricity.

One type of fuel cell being considered in America is claimed to have an efficiency of 75 per cent. in conversion of heat to electricity. The principal problem at the present time appears to be the operating life of the cell—particularly the anode, cathode and solid electrolyte components.

One cell operating under laboratory conditions has a capacity of about 0·75 kW, and there does not appear to be any reason why a large number of such cells cannot be used in parallel to form a power plant for commercial purposes.

Solar Energy Power Plants. According to a recent survey the direct use of the energy of the sun is possible on a limited scale, but there is no prospect at present of developing solar engines that would make a substantial contribution to the total energy demand. The energy of the sun may be made available in another way. Vegetation might provide a factory which, through the intermediary of the carbon-cycle, would make available the sun's energy in a form which could be readily utilized. Unfortunately, the rate of assimilation of carbon-dioxide by existing flora is low. These schemes are perhaps of more immediate application in tropical countries.

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